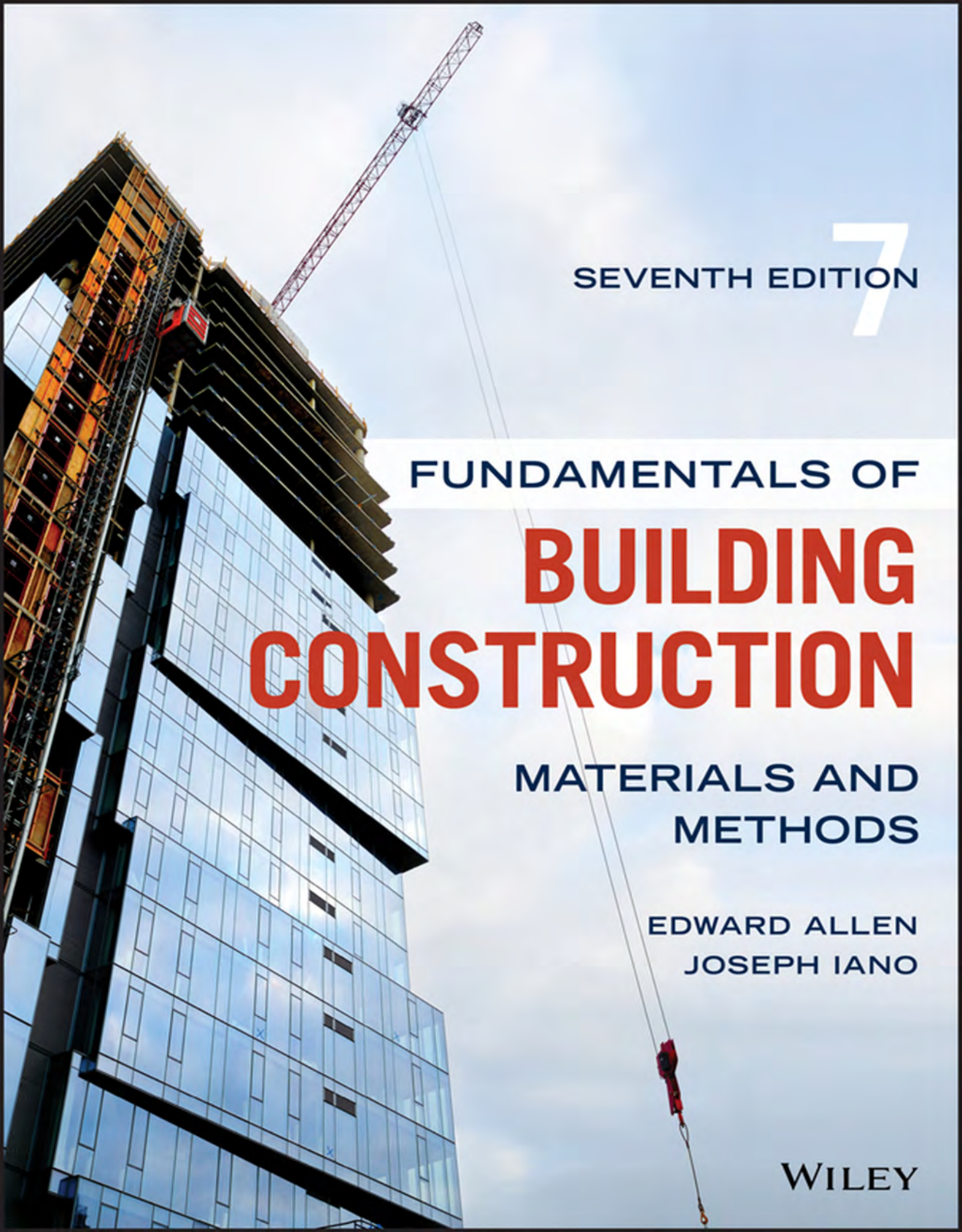


SEVENTH EDITION 7

FUNDAMENTALS OF BUILDING CONSTRUCTION

MATERIALS AND METHODS

EDWARD ALLEN
JOSEPH IANO

WILEY

SHOUT
SHARE
IT

Fundamentals of Building Construction

Fundamentals of Building Construction

Materials and Methods

Seventh Edition

Edward Allen and Joseph Iano

Wiley

Cover image: Stadium Place South Tower, Seattle, by ZGF Architects Photo by Joe Iano
Cover design: Wiley

This book is printed on acid-free paper. ♾

Copyright © 2019 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.

Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 646-8600, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at www.wiley.com/go/permissions.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor the author shall be liable for damages arising herefrom.

For general information about our other products and services, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley publishes in a variety of print and electronic formats and by print-on-demand. Some material included with standard print versions of this book may not be included in e-books or in print-on-demand. If this book refers to media such as a CD or DVD that is not included in the version you purchased, you may download this material at http://booksupport.wiley.com. For more information about Wiley products, visit www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Names: Allen, Edward, 1938- author. | Iano, Joseph, author.
Title: Fundamentals of building construction : materials and methods / Edward Allen and Joseph Iano.
Description: Seventh edition. | Hoboken, New Jersey : Wiley, [2019] | Includes bibliographical references and index. |
Identifiers: LCCN 2018061433 (print) | LCCN 2019000601 (ebook) | ISBN 9781119450245 (Adobe PDF) | ISBN 9781119450252 (ePub) | ISBN 9781119446194 (cloth : acid-free paper)
Subjects: LCSH: Building. | Building materials.
Classification: LCC TH145 (ebook) | LCC TH145 .A417 2019 (print) | DDC 690—dc23
LC record available at https://lccn.loc.gov/2018061433

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Contents

Preface to the Seventh Edition xi

1 Making Buildings 3

Learning to Build 4
Buildings and the Environment 4
- **Other Sustainable Building Programs and Standards 8**

The Work of the Design Professional 12
The Work of the Construction Professional 20
Trends in the Delivery of Design and Construction Services 25

2 Foundations and Sitework 33

Foundation Requirements 34
Earth Materials 35
- **Sustainability and Foundations and Sitework 41**

Earthwork and Excavation 42
Foundations 50
Foundations as Building Enclosure 65
Sitework 72
Designing Foundations 75
Foundations and the Building Code 75

3 Wood 79

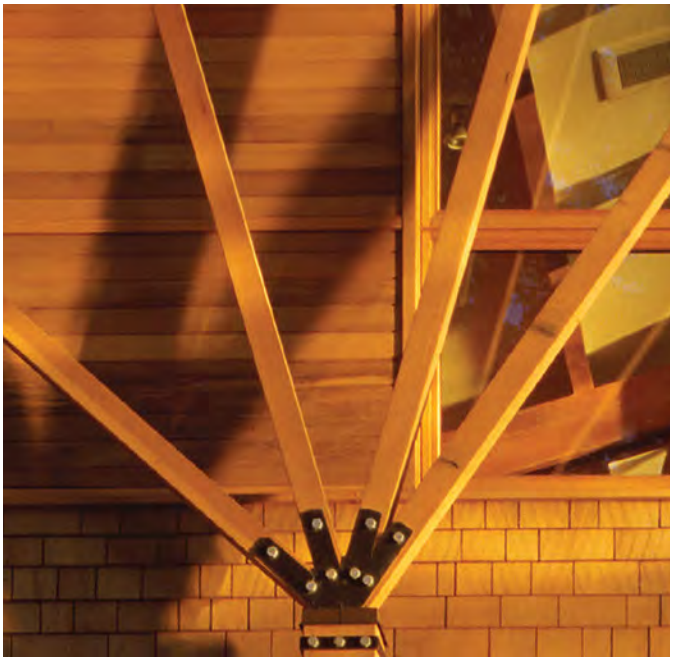
Trees 80
- **Sustainability and Wood 84**

Lumber 84
Wood Products 96
Plastic Lumber 102
Wood Panel Products 102
Protecting Wood from Decay and Fire 106
- **Chemical Wood Preservative Treatments 107**

Wood Fasteners and Adhesives 109
- **Wood Product Adhesives and Formaldehyde 115**

Prefabricated Wood Components 115

CASE STUDY 121
French American School



4 Heavy Timber and Mass Timber Construction 125

Types of Construction 126
- **Sustainability and Heavy Timber and Mass Timber Construction 129**

Fire Resistance of Large Wood Members 131
- **Calculating the Fire Resistance of Wood Members 131**

Traditional Heavy Timber Construction 132
Contemporary Heavy Timber Construction 134
Mass Timber Construction 140
Wood–Concrete Composite Construction 143
Longer Spans in Heavy Timber and Mass Timber 144
- **Preliminary Design of Heavy Timber and Mass Timber Structures 148**

5 Wood Light Frame Construction 151

History 153
Platform Frame 154
- **Sustainability and Wood Light Frame Construction 156**

Foundations for Wood Light Frame Structures 156
Building the Frame 164
Variations on Wood Light Frame Construction 199
- **Preliminary Design of Wood Light Frame Structures 202**

Wood Light Frame Construction and the Building Codes 202
Uniqueness of Wood Light Frame Construction 204

6 Exterior Finishes for Wood Light Frame Construction 211

Protection from the Weather 212
Roofing 213
Windows and Doors 220
- **Paints and Coatings 224**

Siding 228
Corner Boards and Exterior Trim 237
Sealing Exterior Joints 238
- **Sustainability and Paints and Other Architectural Coatings 240**

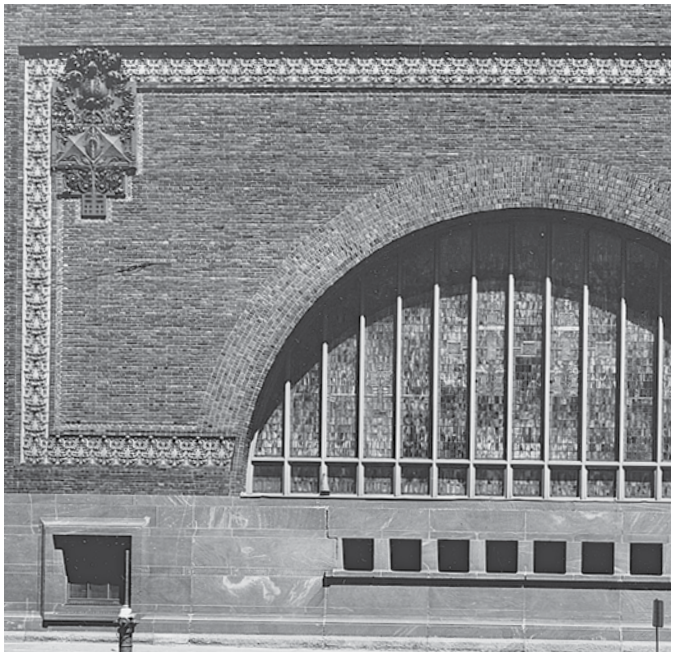
Exterior Painting, Finish Grading, and Landscaping 240
Exterior Construction 240

7 Interior Finishes for Wood Light Frame Construction 245

Completing the Building Enclosure 253
- **Sustainability and Insulation Materials for Wood Light Frame Construction 262**

Wall and Ceiling Finish 264
Millwork and Finish Carpentry 265

■ **Proportioning Fireplaces 266**
■ **Proportioning Stairs 280**
Flooring and Ceramic Tile Work 282
Finishing Touches 284



8 Brick Masonry 289

History 290
Mortar 293
■ **Sustainability and Brick Masonry 296**
Brick 296
Brick Masonry 304
Masonry Wall Construction 319

9 Stone and Concrete Masonry 329

Stone Masonry 330
■ **Sustainability and Stone and Concrete Masonry 343**
Concrete Masonry 348
Other Types of Masonry Units 358
Masonry Wall Construction 359

10 Masonry Wall Construction 363

Types of Masonry Walls 364
■ **Preliminary Design of Loadbearing Masonry Structures 372**
Spanning Systems for Masonry Bearing Wall Construction 372
Detailing Masonry Walls 376
Special Problems of Masonry Construction 380
■ **Movement Joints in Buildings 382**
Masonry Paving 388
Masonry and the Building Codes 389
Uniqueness of Masonry 389

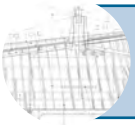
11 Steel Frame Construction 395

History 396
The Material Steel 398
■ **Preliminary Design of Steel Structures 401**
Joining Steel Members 409

Details of Steel Framing 415
■ **Seismic Force Resisting Systems 421**
The Construction Process 426
Fire Protection of Steel Framing 442
Longer Spans and Higher-Capacity Columns in Steel 447
■ **Fabric Structures 454**
■ **Sustainability and Steel Frame Construction 458**
Steel and the Building Codes 459
Uniqueness of Steel 459

12 Light Gauge Steel Frame Construction 467

The Concept of Light Gauge Steel Construction 468
■ **Sustainability and Light Gauge Steel Framing 469**
Light Gauge Steel Framing 470
Other Uses of Light Gauge Steel Framing 479
■ **Preliminary Design of Light Gauge Steel Frame Structures 481**
Insulating Light Gauge Steel Frame Structures 481
Finishes for Light Gauge Steel Framing 482
Advantages and Disadvantages of Light Gauge Steel Framing 482
Light Gauge Steel Framing and the Building Codes 482
■ **Metals in Architecture 484**



CASE STUDY 490
Camera Obscura at Mitchell Park, Greenport, New York

13 Concrete Construction 495

History 496
Cement and Concrete 497
■ **Sustainability and Concrete Construction 500**
Making and Placing Concrete 503
Formwork 507
Reinforcing 508
Concrete Creep 522
Prestressing 522
Concrete Standards 527
Innovations in Concrete 527

14 Sitecast Concrete Framing Systems 533

Casting a Concrete Slab on Grade 535
Casting a Concrete Wall 540
Casting a Concrete Column 544
One-Way Floor and Roof Framing Systems 545
Two-Way Floor and Roof Framing Systems 555
Sitecast Posttensioned Framing Systems 561
Other Types of Sitecast Concrete 562
■ **Cutting Concrete, Stone, and Masonry 568**
Longer Spans in Sitecast Concrete 570
Designing Economical Sitecast Concrete Buildings 572
■ **Preliminary Design of Sitecast Concrete Structures 574**
Sitecast Concrete and the Building Codes 575
Uniqueness of Sitecast Concrete 575

15 Precast Concrete Framing Systems 583

Precast, Prestressed Concrete Structural Elements 586
- **Preliminary Design of Precast Concrete Structures 587**

Assembly Concepts for Precast Concrete Buildings 588
Manufacture of Precast Concrete Structural Elements 589
Joining Precast Concrete Members 595
- **Fastening to Concrete 596**

Composite Precast/Sitecast Concrete Construction 609
The Construction Process 609
- **Sustainability and Precast Concrete Framing Systems 610**

Precast Concrete and the Building Codes 611
Uniqueness of Precast Concrete 611

16 Designing the Building Enclosure 621

Functional Requirements of the Building Enclosure 622
- **Sustainability and the Building Enclosure 629**

Keeping Water Out 629
Controlling the Flow of Heat 634
Controlling Air Leakage 636
Controlling the Diffusion of Water Vapor 638
Sealing Joints in the Exterior Wall 641

17 Roofing 649

Low-Slope Roofs 651
- **Sustainability and Roofing 656**

Steep Roofs 671
Cool Roofs 684
- **Dissimilar Metals and Galvanic Corrosion 686**

Green Roofs 688
Photovoltaic Systems 690
Roofing and the Building Codes 691

18 Glass and Glazing 695

History 696
The Material Glass 699
- **Sustainability and Glass 700**

■ **Other Types of Glass 711**
Glazing 712
Glass and Energy 721
Glass and the Building Codes 721

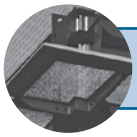
CASE STUDY 726
Skating Rink at Yerba Buena Gardens

19 Windows and Doors 731

Windows 732
■ **Plastics in Building Construction 739**
■ **Sustainability and Windows and Doors 745**
Doors 745
Other Window and Door Requirements 752

20 Cladding with Masonry and Concrete 759

Masonry Veneer Curtain Walls 760
Stone Curtain Walls 767
Precast Concrete Curtain Walls 771
Exterior Insulation and Finish Systems 774



CASE STUDY 778
Seattle University School of Law

21 Cladding with Metal and Glass 783

Aluminum 784
■ **Sustainability and Cladding with Metal and Glass 789**
Aluminum and Glass Framing Systems 791
An Outside Glazed Curtain Wall System 797
Double-Skin Facades 800
Sloped Glazing Systems 800
The Curtain Wall Design Process 801
Metal Panel Cladding 801

22 Selecting Interior Finishes 807

Installation of Mechanical and Electrical Services 808
■ **Sustainability and Interior Finishes 810**
The Sequence of Interior Finishing Operations 810
Selecting Interior Finishes 811
■ **Other Surface Flammability Criteria 815**
Long-Term Trends in Interior Finish Systems 817

23 Interior Walls and Partitions 821

Interior Walls and Fire Criteria 822
Partition Framing 823
■ **Sustainability and Gypsum and Other Wall Covering Products 826**
Plaster Partitions 827
Gypsum Board Partitions 837
■ **Plaster Ornament 838**
Masonry Partitions 848
Wall and Partition Facings 848

24 Finish Ceilings and Floors 855

Finish Ceilings 856
Types of Ceilings 857
■ **Sustainability and Finish Ceilings and Floors 866**
Finish Flooring 867
Types of Finish Flooring Materials 871

Appendix 884

Glossary 886

Index 917

Preface to the *Seventh Edition*

First published over a quarter century ago, *Fundamentals of Building Construction: Materials and Methods* has wrought a revolution in building construction education. It made a previously unpopular area of study not merely palatable but vibrant and well liked. It has taken a practical, and at times undervalued, body of knowledge and made it widely recognized as centrally relevant to good building design. It has replaced dry, unattractive books with a well-designed, readable volume that students value and keep as a reference work. It was the first book in its field to be evenhanded in its coverage and profusely and effectively illustrated throughout. It was the first to release the teacher from the burden of explaining everything in the subject, thereby freeing class time for discussions, case studies, field trips, and other enrichments.

Gaining a useful knowledge of the materials and methods of building construction is crucial and a necessity for the student of architecture, engineering, or construction, but it can be a daunting task. The field is broad, diverse, complex, and under constant change, such that it seems impossible to ever master. This book has gained its preeminent status as an academic text in this field because of its logical organization, outstanding illustrations, clear writing, and distinctive philosophy.

It is *integrative*, presenting a unified narrative that interweaves issues of building science, material properties, building craft, and legal constraints so that the reader does not have to refer to separate parts of the book to make the connections among these issues. The elements of building construction are presented as whole working systems rather than disconnected parts.

It is *selective* rather than comprehensive. This makes it easy and pleasant for the reader to gain a working knowledge that can later be expanded, without piling on so many facts and figures that the reader becomes discouraged from learning about construction. This book deals, as its subtitle indicates, with fundamentals.

It is *empowering* because it is structured around the process of designing and constructing buildings. The student of architecture will find that it features the design possibilities of the various materials and systems. Students interested in building or managing the construction process will find its organization around construction sequences to be invaluable.

This seventh edition incorporates extensive updates and revisions. Chapter 4, now entitled "Heavy Timber and Mass Timber Construction," covers new and exciting developments in the design and construction of tall wood buildings. We discuss mass timber construction methods, upcoming building code provisions that will regulate this new construction type, and more. A rewritten chapter, now titled "Designing the Building Enclosure," comprehensively addresses in one place all aspects of building enclosure ("building envelope") science, making this important material easier for students to access and instructors to teach. In Chapter 1, our coverage of sustainable building has kept pace with this evolving topic, including, for example, an expanded discussion of the increasingly sophisticated tools available for assessing the environmental and health impacts of building materials. Throughout the remainder of the text the reader will find extensive updates in content, along with new illustrations and photographs, reflecting the latest practices and developments in the field.

In this edition, a special thank-you goes to Fast + Epp engineers, and in particular, Davin Lewis, P.E., of that firm, for their generous advice and assistance. Thank you as well to David Barber of Arup and Colin Shane of RDH for their efforts. Lastly, we offer our thanks to the many teachers, students, and professionals who have purchased and used this work. Your satisfaction is our greatest reward, your loyalty is greatly appreciated, and your comments are always welcome!

—E.A., Weyland, Massachusetts
—J.I., Seattle, Washington

Additional resources for instructors and students are readily available via the companion website: www.wiley.com/go/allenfbc7e.

Icons throughout the text indicate SketchUp exercises and animations which are also available for download on the companion website.

Fundamentals of Building Construction

1

Making Buildings

- **Learning to Build**
- **Buildings and the Environment**
  - Sustainable Buildings
  - Sustainable Building Materials
  - The Impact of Sustainable Buildings
- **The Work of the Design Professional**
  - Environmental and Land Use Regulations
  - Building Codes
  - Other Constraints
  - Construction Standards and Information Resources
- **The Work of the Construction Professional**
  - Providing Construction Services
  - Construction Scheduling
  - Managing Construction
- **Trends in the Delivery of Design and Construction Services**
  - Fostering Collaboration
  - Improving Productivity
  - Advances in Information Technology

Other Sustainable Building Programs and Standards

An ironworker connects a steel wide-flange beam to a column.
(Courtesy of Bethlehem Steel Company.)

We build to satisfy our practical and spiritual needs. Not all human activity can take place outdoors. We need shelter from sun, wind, rain, and snow. We need dry, level surfaces for our activities. On these sheltered surfaces, we need air that is warmer or cooler, more or less humid, than outdoors. We need less light by day, and more by night, than is offered by the natural world. We need services that provide energy, communications, water, and disposal of wastes. And we need structures that house and express our cultural and spiritual aspirations. So, we gather materials and assemble them into the constructions we call buildings in an attempt to satisfy these needs.

Learning to Build

This book is about the materials and methods of building construction. Throughout it, alternative ways of building are described: different structural systems, different methods of building enclosure, and different interior finishes, each with characteristics that distinguish it from the alternatives. Sometimes a choice between alternatives is based on visual characteristics, such as when a particular finish material is preferred for its surface character and beauty, or when a material such as concrete is selected over steel for its massiveness and plasticity. Sometimes choices are purely technical, such as the selection of a membrane that is impervious to water for a low-slope roof, or when a particular method of masonry wall reinforcing is selected to provide resistance to earthquake forces. Choices of materials and building systems may be made with the goal of minimizing environmental impacts or they may be dictated by regulations intended to protect public safety and welfare. Construction costs, energy efficiency, durability, and many other factors come into consideration.

This textbook will start you down the path of becoming skilled at making such choices. But it is incumbent upon the student to go beyond what is provided here—to other books, product literature, trade publications, professional periodicals, websites, and especially the design office, workshop, and building site. One must learn how materials feel in the hand; how they look in a building; how they are manufactured, worked, and put in place; how they perform in service; how they age with time. One must become familiar with the people and organizations that produce buildings—the architects, engineers, product manufacturers, materials suppliers, contractors, subcontractors, workers, inspectors, managers, and building owners—and learn to understand their respective methods, problems, and points of view. There is no other way to gain the breadth of information and experience necessary than to get involved in the art and practice of building.

In the meantime, this long and hopefully enjoyable process of education in the materials and methods of building construction can begin with the information presented within this text.

Go into the field where you can see the machines and methods at work that make the modern buildings, or stay in construction direct and simple until you can work naturally into building-design from the nature of construction.

—Frank Lloyd Wright, "To the Young Man in Architecture," 1931

Buildings and the Environment

In constructing and occupying buildings, we expend large quantities of the earth's resources and generate a significant portion of its environmental pollution. The construction and operation of buildings account for as much as a third of the world's energy consumption and carbon dioxide (a global warming gas) emissions. In the United States, building operation and construction consume between a third and a half of the country's energy, 70 percent of its electricity, 12 percent of its potable water, 30 percent of its raw materials, and a third of its solid waste. And these same activities are responsible for as much as 45 percent of the country's carbon dioxide emissions. Buildings are also significant emitters of particulates and other air pollutants. In short, building construction and operation contribute to many forms of environmental degradation and place a significant burden on the earth's resources.

In 1987, the United Nations report "Our Common Future" provided a concise definition of *sustainable development*: building to meet the needs of the present generation without compromising the ability of future generations to meet their own needs. But, by consuming irreplaceable fossil fuels and other nonrenewable resources, by building in sprawling patterns on prime agricultural land, by using destructive land development and forestry practices that degrade natural ecosystems, by generating substances that pollute water, soil, and air, and by generating copious amounts of waste materials that are eventually incinerated or buried in the earth, we have been building in a manner that will make it increasingly difficult for our children and their children to meet their needs for communities, buildings, and healthy lives. Sustainable building construction demands a more symbiotic relationship between people, buildings, communities, and

FIGURE 1.1
The Bullitt Center, Seattle, designed by architect Miller Hull Partnership, was the first commercial building to achieve Living Building certification in 2015. This building generates as much as 60 percent more electricity than it uses and consumes less than one-quarter of the energy of a typical U.S. office building. *(Photo by Joe Iano.)*

the natural environment. Sustainable buildings—in both their construction and operation—must use less energy, consume fewer resources, cause less pollution of the air, water, and soil, reduce waste, discourage wasteful land development practices, and contribute to the protection of natural environments and ecosystems.

Over the decades since the release of "Our Common Future," the practice of sustainable design and construction, also called *green building*, has grown. The understanding of the interplay between buildings and the environment has deepened, and standards for assessing the sustainability of materials and construction practices have grown in number and matured in approach. The definition of sustainability has expanded to address the human health impacts of buildings and to include issues of social and economic fairness. And the expectations for the performance of sustainable buildings have, in some cases, moved from doing less environmental harm to doing no harm or even undoing previous such harms. That is, a sustainable building can be designed to consume no energy or even generate excess energy, cause no air pollution or even help clean the atmosphere, and so on (Figure 1.1).

Also during this time, interest in and adoption of green building has broadened among public agencies, private owners, and the users of buildings. The design and construction industry has become more skillful at applying green practices, and sustainable building has become more integrated with mainstream practice. As a result, sustainable building performance continues to improve while the premium in cost and effort to design and construct such buildings continues to decline.

Sustainable Buildings

Sustainable building requires a holistic, interdisciplinary approach to design and construction. For example, one project goal may be to provide natural daylighting, as a means to improving productivity and the well-being of building occupants. Good daylighting design reduces reliance on electric lighting. This, in turn, reduces electricity consumption and excess heat generated by the electric lights. This, then, reduces cooling loads and allows the building's cooling system to be reduced in capacity and physical size. Daylighting design can also influence building siting and shape, the arrangement and sizes of spaces within the building, and the building structure and enclosure. As a result of the decision to provide natural daylighting, many building systems are impacted, and many opportunities for cost savings, reductions in energy consumption, improvements in occupant health and comfort, and lessening of environmental impacts are created.

This kind of design thinking, called *integrated design process* (*IDP*), is a whole-systems way of working that breaks down traditional boundaries between disciplines and parts of the work. All key members of the design, construction, and owner groups are brought together. A clear vision and goals are established. The process spans from the earliest conceptual phase through design, construction, and post-occupancy (the operational phase once the project is completed). And a collaborative, interdisciplinary

LEED for New Construction and Major Renovation

Project Checklist

Project Name

Date

Y	?	N			
			Credit 1	Integrative Process	1
			Location and Transportation	Possible Points:	16
			Credit 1	LEED for Neighborhood Development Location	16
			Credit 2	Sensitive Land Protection	1
			Credit 3	High Priority Site	2
			Credit 4	Surrounding Density and Diverse Uses	5
			Credit 5	Access to Quality Transit	5
			Credit 6	Bicycle Facilities	1
			Credit 7	Reduced Parking Footprint	1
			Credit 8	Green Vehicles	1
			Sustainable Sites	Possible Points:	10
Y			Prereq 1	Construction Activity Pollution Prevention	Required
			Credit 1	Site Assessment	1
			Credit 2	Site Development—Protect or Restore Habitat	2
			Credit 3	Open Space	1
			Credit 4	Rainwater Management	3
			Credit 5	Heat Island Reduction	2
			Credit 6	Light Pollution Reduction	1
			Water Efficiency	Possible Points:	11
Y			Prereq 1	Outdoor Water Use Reduction	Required
Y			Prereq 2	Indoor Water Use Reduction	Required
Y			Prereq 3	Building-Level Water Metering	Required
			Credit 1	Outdoor Water Use Reduction	2
			Credit 2	Indoor Water Use Reduction	6
			Credit 3	Cooling Tower Water Use	2
			Credit 4	Water Metering	1
			Energy and Atmosphere	Possible Points:	33
Y			Prereq 1	Fundamental Commissioning and Verification	Required
Y			Prereq 2	Minimum Energy Performance	Required
Y			Prereq 3	Building-Level Energy Metering	Required
Y			Prereq 4	Fundamental Refrigerant Management	Required
			Credit 1	Enhanced Commissioning	6
			Credit 2	Optimize Energy Performance	18
			Credit 3	Advanced Energy Metering	1
			Credit 4	Demand Response	2
			Credit 5	Renewable Energy Production	3
			Credit 6	Enhanced Refrigerant Management	1
			Credit 7	Green Power and Carbon Offsets	2

			Materials and Resources		Possible Points: 13
Y			Prereq 1	Storage and Collection of Recyclables	Required
Y			Prereq 2	Construction and Demolition Waste Management Planning	Required
			Credit 1	Building Life-Cycle Impact Reduction	5
			Credit 2	Building Product Disclosure and Optimization — Environmental Product Declarations	2
			Credit 3	Building Product Disclosure and Optimization — Sourcing of Raw Materials	2
			Credit 4	Building Product Disclosure and Optimization — Material Ingredients	2
			Credit 5	Construction and Demolition Waste Management	2
				Indoor Environmental Quality	Possible Points: 16
Y			Prereq 1	Minimum Indoor Air Quality Performance	Required
Y			Prereq 2	Environmental Tobacco Smoke Control	Required
			Credit 1	Enhanced Indoor Air Quality Strategies	2
			Credit 2	Low-Emitting Interiors	3
			Credit 3	Construction Indoor Air Quality Management Plan	1
			Credit 4	Indoor Air Quality Assessment	2
			Credit 5	Thermal Comfort	1
			Credit 6	Interior Lighting	2
			Credit 7	Daylight	3
			Credit 8	Quality Views	1
			Credit 9	Acoustic Performance	1
				Innovation	Possible Points: 6
			Credit 1	Innovation	5
			Credit 2	LEED Accredited Professional	1
				Regional Priority	Possible Points: 4
			Credit 1	Regional Priority: Specific Credit	1
			Credit 2	Regional Priority: Specific Credit	1
			Credit 3	Regional Priority: Specific Credit	1
			Credit 4	Regional Priority: Specific Credit	1
				Total	Possible Points: 110

Certified 40 to 49 points Silver 50 to 59 points Gold 60 to 79 points Platinum 80 to 110

FIGURE 1.2
The LEED v4 New Construction and Major Renovation Project Checklist. *(Courtesy of U.S. Green Building Council.)*

approach is used that maximizes opportunities for synergies and innovation.

In the United States, the most widely applied program for building sustainability is the U.S. Green Building Council's *Leadership in Energy and Environmental Design*, or *LEED*®, rating system. LEED for New Construction and Major Renovation groups sustainability goals into eight broad categories addressing areas such as site selection and development, energy efficiency, conservation of materials and resources, and others (Figure 1.2). Within each category are mandatory *prerequisites* and optional *credits* that contribute points toward a building's overall rating. During the design and construction process, the achievement of prerequisites and credits is documented and submitted to the Green Building Council, which then makes the certification of the project's LEED compliance after construction is completed. Depending on the point total achieved, four levels of sustainable performance are recognized, including, in order of increasing performance, Certified, Silver, Gold, and Platinum. The LEED rating system is itself voluntary. It is used when adopted by a private building owner or mandated by a public building agency.

The Green Building Council also provides rating systems for existing buildings, commercial interior

buildouts, building core and shell construction, schools, retail buildings, healthcare facilities, homes, neighborhood developments, building operations and maintenance, and other project types. Through affiliated organizations, LEED is also implemented in Canada and other countries.

The International Living Future Institute's *Living Building Challenge*™ sets a higher standard for sustainable building. This program aspires to move past making buildings that do less environmental harm to those that do no harm or even improve the natural environment and our well-being. For example, a building constructed and operated to this standard will (when considered on an annualized basis) generate all its own energy from on-site renewable resources, consume no fresh water, and have no greenhouse gas emissions.

The Living Building Challenge contains seven categories, called Petals, including Place, Water, Energy, Health & Happiness, Materials, Equity, and Beauty. Within these are 20 *Imperatives*, such as net zero energy, appropriate sourcing of materials, embodied carbon footprint, and more. There are three certification levels: Living Building Certification meets all imperatives appropriate to the building type, Petal Certification signifies a lower level of partial compliance, and Zero Energy Certification applies to projects that generate all energy on site without reliance on combustion processes. Certification occurs after a building has been operational for at least one year, when its real-world performance can be assessed. The Living Building Challenge can also be applied to other types of construction and development, such as neighborhoods, landscape and infrastructure projects, and building renovations.

Sustainable Building Materials

Describing Sustainable Materials

Designing sustainable buildings requires access to information about the environmental and health impacts of the materials used in their construction. For example, when selecting a material, the designer might ask: Does its manufacture depend on the extraction of nonrenewable resources, or is it made from recycled or rapidly renewable materials? Is additional energy required to ship this material from a distant location, or can it be obtained from local sources? Does the material contain toxic ingredients or generate unhealthful emissions, or is it free of such health concerns?

Information about building materials and products can come from different sources and take various forms:

- It may be self-reported by the product manufacturer, or it may come from an independent, trusted third party.
- It may take the form of a neutrally expressed, transparent disclosure of material attributes, or it may gauge the merits (or demerits) of such attributes and provide a rating of the material's sustainability.
- It may address a limited scope of concerns, or it may describe the full range of impacts of a material throughout its life cycle from raw materials extraction to end-of-life disposal or repurposing.

The industry-standard *Product Data Sheet* (*PDS*) is a simple example of manufacturer self-reported information. The PDS provides a description of a product, its material makeup and physical properties, and guidelines for use. It may also include information relevant to sustainability concerns, although this is not its primary purpose. The scope of information provided in a PDS is left entirely to the manufacturer, and the information is not independently verified.

Other Sustainable Building Programs and Standards

There are many programs and standards offering alternative pathways to sustainable building construction, suitable to various building types, objectives, and construction markets. For example, the U.S. National Association of Home Builders' National Green Building Standard addresses both single-family and multi-unit residential building types. The International Green Construction Code is a model code that puts green building standards into a legally enforceable format that is useful for municipalities that wish to mandate sustainable construction. CALGreen is the sustainable construction code for the state of California. Green Globes certifies new and existing sustainably designed buildings in the United States and Canada. The Building Research Establishment Environmental Assessment Method, or BREEAM, does the same for buildings constructed in the United Kingdom and other European countries. The Passive House Standard, implemented in many places around the globe, emphasizes dramatic reductions in the energy consumption of residential and commercial buildings. The International WELL Building Institute's WELL Building Standard certifies building construction with regard to human health and well-being criteria. In addition, professional organizations and government agencies offer programs to support sustainable building, such as the Architecture 2030 Challenge and ASHRAE's Standard for the Design of High-Performance Green Buildings, to name just two.

Environmental labels, also called *ecolabels*, are third-party environmental ratings. An example is the Green Seal Standard GS-11 for Paints and Coatings. Green Seal is an independent organization that develops sustainability standards and certifications. For a paint product to be certified to its standard, the product must meet minimum performance criteria, be free of toxic ingredients, and not exceed content limits on *volatile organic compounds* (*VOCs*). (VOCs are air polluting and unhealthful chemical compounds that are released in particularly heavy concentrations from wet-applied products as they dry.) By relying on this certification, the designer can confidently make environmentally responsible choices, without having to perform in-depth investigations of individual products.

Product disclosures are another form of reporting that provide transparent information about material ingredients and manufacturer practices. For example, the International Living Future Institute's Declare label describes a product's origins, its material ingredients, and end-of-life disposal or recycling options. By providing this information in a standardized format, designers can more easily compare the relative attributes of alternative materials or products and make better-informed choices. Like a Product Data Sheet, the Declare label is self-reported by manufacturers, albeit with an option for independent auditing to verify accuracy. Unlike ecolabels, product disclosures do not rate the sustainability of the product—it remains up to the user to interpret the information provided for this purpose.

Environmental Product Declarations (*EPDs*) describe the full, life-cycle environmental impacts of building materials and products. An example is the Western Red Cedar Lumber Association's Typical Red Cedar Decking Product Declaration. This 10-page document describes this product's material characteristics and quantifies—in some detail—environmental impacts throughout its life. For example, for every 1 square meter (11 square feet) of decking harvested, milled, trucked to the construction site, installed, maintained through its useful life, and then disposed of at the end of its life, this declaration reports the following:

- 73 MJ (70,000 BTU) of nonrenewable energy consumed
- 6.8 kg (15 pounds) of CO_2 equivalent *global warming potential*
- 86 L (23 gallons) of fresh water consumed

Additional information in the report quantifies materials consumption, smog production, ozone depletion, acidification and eutrophication potential, waste materials generated, and more. Information about the standards to which this information is prepared and independent verification of the results are also included. While this document does not provide an environmental rating, it can be used, for example, in comparing Western red cedar to some other material, such as recycled plastic decking, to assess the relative environmental consequences of choosing one of these materials over the other.

In relative infancy are *Environmental Building Declarations*, or *EBD*s. As life-cycle data become available for the majority of materials and products used in construction, the same type of life-cycle analysis can be applied to whole buildings, allowing the environmental impacts of alternative building designs to be meaningfully compared.

Much of the environmental reporting provided by product manufacturers is developed according to the international series of standards designated *ISO 14020*, which establish guidelines for the development and use of environmental labels and declarations. By relying on information produced to common, accepted standards, designers and builders can have the greatest confidence in the consistency and relevance of the information provided.

The Material Life Cycle and Embodied Impacts

Preparation of environmental product and building declarations depends on the accounting of the environmental impacts of materials and products throughout their life cycles. This begins with raw materials extraction, continues with manufacture, construction, and use, and finishes at end of life when a material is disposed of or put to a new use. Such a *life-cycle analysis* (*LCA*), or *cradle-to-grave analysis*, is one of the most comprehensive methods for quantifying the environmental impacts associated with materials and buildings. Through each life-cycle stage, impacts are tallied: How much fossil fuel, electricity, water, and other materials are consumed? How much solid waste, global warming gasses, and other air and water pollutants are generated? The total of all these impacts describes the *environmental footprint* of the material (Figure 1.3).

The concept of embodied energy also derives from life-cycle analysis. *Embodied energy* is the sum total of energy consumed during a material's life cycle. Because energy consumption frequently correlates with the consumption of nonrenewable resources and the generation of greenhouse gasses, it is easy to assume that materials with lower embodied energy are better for the environment than others with greater embodied energy. However, in making such comparisons, it is important to be sure that the comparison is functionally equivalent. For example, a material with an embodied energy of 10,000 BTU per pound is not necessarily environmentally preferable to another with an embodied energy of 15,000 BTU per pound, if 2 pounds of the prior material are required to accomplish the same purpose as 1 pound of the latter. The types of energy consumed for each material, such as fossil, nuclear, or renewable,

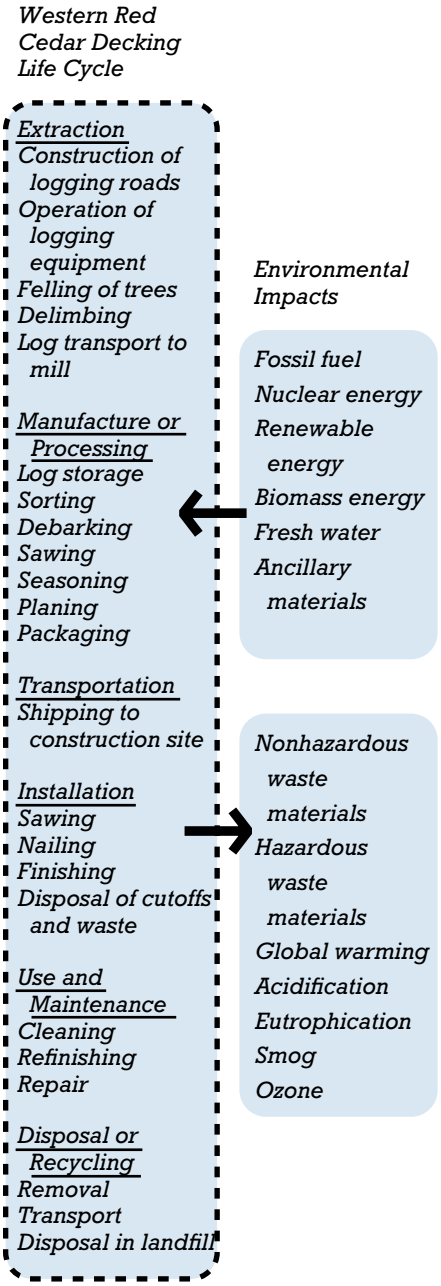


FIGURE 1.3

Life-cycle analysis of Western red cedar decking. The underlined life-cycle stages (Extraction, Manufacture or Processing, etc.) are applicable to any building construction material LCA. The activities listed under each stage here are specific to the example of Western red cedar decking. For other materials, other activities would be listed. The right-hand column lists the types of environmental impacts associated with this material, both resources consumed (such as energy and water) and pollutants and wastes emitted (such as global warming gasses and nonhazardous waste). Though not included here, the LCA also quantifies these impacts so that one material can be readily compared with another.

should also be considered, as impacts differ from one energy source to another.

Embodied energy and other life-cycle effects may sometimes be calculated for only a part of the material life cycle. A *cradle-to-gate analysis* begins with materials extraction but extends only as far as when the material leaves the factory, excluding the effects of transportation to the building site, installation, use, maintenance, and disposal or recycling. Though less comprehensive, such analyses can still provide a useful basis for comparison between products. For example, for many materials, the difference in embodied energy between a cradle-to-grave and cradle-to-gate analysis is small, as most of the energy expenditure occurs prior to the material's installation, use, and eventual disposal.

The concept of embodied effects can also be applied to other measured inputs or outputs from a life-cycle analysis. For example, *embodied water* refers to the fresh water consumed as a consequence of building with a particular material.

While life-cycle analysis represents the most generally comprehensive materials assessment method currently available, it does not necessarily address all impacts arising from the use of a material or product. LCA of wood products, for example, does not capture the loss of biodiversity, decreased water quality, or soil erosion caused by poor forestry practices. In this case, these concerns are better addressed by sustainable forestry certification programs. Or, although global warming potential is quantified in a material environmental product declaration, the ultimate consequences of that effect for ecosystems, wildlife populations, and human well-being are not fully described.

Health Impacts of Building Materials

Much like the sources of information available for the assessment of material environmental impacts, information useful to understanding the human health-related impacts of materials and products can also be provided in various formats.

Similar to environmental product declarations, *health product declarations* (*HPDs*) may be prepared by the product manufacturer or an independent agency. The standard for creating HPDs is defined by the HPD Collaborative, an independent organization with representation from many construction industry stakeholders. HPDs provide reliable and consistent information about material ingredients and associated human and environmental health hazards. They list the material contents of the product being reported and indicate associated hazards, such as the presence of persistent bio-accumulative toxic compounds, carcinogens, respiratory irritants, neurotoxins, and more. Like EPDs, HPDs are not a certification or rating tool—that is, they do not, in themselves, assess the healthfulness of a product. They do, however, provide important information in a standard format that can be used to make health-related comparisons.

Other Sustainable Material Attributes

Products with a high *recycled materials content* help to divert waste materials that would otherwise be disposed of in landfills or by incineration. Recycled content can be distinguished as either preconsumer or postconsumer. *Preconsumer recycled materials* originate as byproducts of manufacturing processes. For example, when a glass manufacturer reclaims broken glass

during its manufacture and reprocesses this waste into new glass, this is preconsumer recycled waste. *Postconsumer recycled materials* are generated by end users of a material. A gypsum board manufacturer recycling used newsprint into paper facing for its board products is an example of postconsumer recycled wasted. When assessing recycled content in the LEED system, preconsumer waste is counted at only half of its weight or cost, while postconsumer waste is counted at its full value.

Bio-based materials are produced by agricultural or animal biological processes. Examples include cornstarch derived from grain and used as an ingredient in the manufacture of gypsum wallboard, or resins made from wood lignin, starch, or other plant proteins used as substitutes for traditional petroleum-derived resins in the manufacture of composite wood products. Bio-based materials are biodegradable or compostable, and carbon-neutral (meaning they have little if any impact on global warming). Their production can contribute to employment in rural areas. And when cultivated and harvested in a sustainable manner, they are a renewable resource that can reduce dependence on irreplaceable fossil fuels. However, the production of bio-based materials occupies arable land and requires fresh water, fertilizer or feedstock, and energy. Determining the potential benefit of a bio-based material requires analysis of the environmental impacts throughout the material's life cycle and comparing those to the impacts of alternative materials.

Some bio-based materials are *rapidly renewable*, that is, they are grown and harvested in a relatively short time span. LEED defines rapidly renewable materials as those harvested within a 10-year or shorter cycle.

Regional, or *locally sourced*, *materials* are produced near the construction site. Relying on locally sourced materials reduces energy consumption and emissions associated with materials transportation. And it contributes to the economic well-being of the community in which the building is being constructed. LEED defines regional materials as those extracted, manufactured, and purchased within 100 miles (160 km) of the construction site.

Materials Assessment Within Sustainable Building Programs

Within LEED, the Living Building Challenge, and other sustainable building programs, material attributes can be evaluated in relation to a range of environmental, health, and social impact considerations.

Energy performance. Appropriate materials choices and design can reduce heat losses through the building enclosure, moderate peak heating and cooling loads, and support passive heating and cooling strategies, all of which can contribute to reductions in building energy use.

Building and material life-cycle impacts. Adaptive reuse of existing buildings, salvaging materials from existing buildings for use in new ones, and design of new structures for future disassembly and materials repurposing are ways to reduce the demand for new raw materials and reduce the volume of waste going to landfills or incineration.

Life-cycle analysis reveals the fullest range of environmental impacts and embodied attributes of materials used in building construction. As the energy required to operate buildings continues to decrease, embodied energy and global warming potential of materials themselves are becoming a larger share of a building's energy consumption and global warming profile, and increasingly important targets for continued reductions in these measures.

Material and production attributes. Transparently disclosing material ingredients, recycled content, rapidly renewable or bio-based materials content, and the geographic source of raw materials encourages the selection of products that reduce environmental impacts. The Declare label, previously discussed, is one such example of a materials disclosure. Another is the Cradle to Cradle Products Innovation Institute's Cradle to Cradle Certification, which provides information about material ingredients, reutilization, and environmental impacts.

Unhealthy materials and emissions. Health-related disclosures can identify material ingredients or compounds used in manufacture that are hazardous to humans or the environment. Health Product Declarations provide transparent disclosure, but without rating. The Living Building Challenge *Red List* identifies materials to be excluded from Living Buildings because these materials are severely polluting, bio-accumulating, or harmful to factory workers, construction workers, or building occupants.

Coatings, sealants, adhesives, wood composites, insulation materials, wall and floor coverings, ceiling materials, and furniture are just some of the potential sources of chemical air pollutants that can be harmful to construction workers or building occupants. For wet-applied materials, in which the majority of VOC emissions occur shortly after the product is installed, the chemical VOC content is limited and may be self-reported by the manufacturer or established by third-party certification. For broader, general emissions compliance of materials and products, third-party testing is required by both LEED and the Living Building Challenge.

Responsible industry practices and social impacts. Manufacturers may self-report or provide independently verified information about raw materials extraction, land use, labor practices, community

relations, and manufacturing processes. For example, the Forest Stewardship Council certifies sustainable forestry and timber harvesting operations. The Natural Stone Council's 373 Sustainability Assessment for Natural Dimension Stone does the same for sustainable quarrying and production of stone.

The International Living Future Institute's JUST program provides a format for product manufacturers to disclose information about social justice practices, such as supportive employee policies, local community support, and socially responsible activities. LEED also recognizes company efforts to address local or regional social and economic priorities.

The Impact of Sustainable Buildings

Sustainable building practice is producing measurable, positive results in building performance. Post-occupancy evaluations of U.S. buildings constructed to LEED standards show reductions in energy consumption and greenhouse gas emissions in the range of 25 to 35 percent in comparison to national averages. Additional improvements also are seen in such areas as reduced water consumption, lowered operating costs, increased occupant satisfaction, higher property values, and more. Sustainable building also creates new challenges. New or reformulated materials may prove to be less durable than those they replace. Innovative products from unique sources may be difficult to source or more costly. Or inexperience with green building technologies may lead to design or construction errors. Ensuring that sustainable buildings meet their performance expectations is another important challenge. While average performance, as noted above, exceeds that of conventional buildings, it is also true that the performance of individual buildings deviate greatly from these averages. And, while many green buildings do outperform conventional buildings, a significant number also underperform expectations.

Building commissioning (abbreviated *Cx*) is a process used to ensure that performance expectations are realized in finished buildings. Commissioning begins with the definition of performance objectives at the start of design. As design progresses, these objectives are used to guide decision-making and review progress at interim milestones. Close to the end of construction, actual performance is verified through on-site testing. Finally, operational guidance is provided to ensure that the finished, occupied building will continue to perform as intended. Building commissioning is traditionally associated with the testing and verification of heating, ventilating, and air conditioning systems in new buildings. With sustainable design, the emphasis is on integrated, whole-building performance, addressing a broader range of building systems and objectives. An effective, fully documented commissioning process is a prerequisite to achieving LEED certification. Under the Living Building Challenge, a full year of operational data, showing successful compliance with design and performance objectives, must be collected before Living Building certification is awarded.

The Work of the Design Professional

A building begins as an idea in someone's mind, a desire for new and ample accommodations for a family, many families, an organization, or an enterprise. For any but the smallest buildings, the next step for the owner of the prospective building is to engage the services of building design professionals. An architect helps to organize the owner's ideas about the new building while various engineering specialists work out concepts and details of foundations, structural support, and mechanical, electrical, and communications services.

The architect should have construction at least as much at his fingers' ends as a thinker his grammar.

—Le Corbusier, *Towards a New Architecture*, 1927

This team of designers, working with the owner, then develops the scheme for the building in progressively finer degrees of detail. *Drawings*, primarily graphic in content, and *specifications*, mostly written, are produced by the architect/engineer team to describe how the building is to be made and of what. These drawings and specifications, collectively known as the *construction documents*, are submitted to the local government building authorities, where they are checked for conformance with various codes and regulations before a permit is issued to build. A general contractor is selected, who then plans the construction work in detail. Once construction begins, the general contractor oversees the construction process and hires the subcontractors who carry out many portions of the work, while the building inspector, architect, and engineering consultants observe the work at intervals to be sure that it is completed according to plan. Finally, construction is finished, the building is made ready for occupancy, and that original idea—which may have been initiated years earlier—is realized.

Environmental and Land Use Regulations

For many buildings, the first step in the legal approval process may be an environmental impact assessment. Concerns related to both the natural and built environments may be addressed, including, for example, potential impacts on water resources,

natural habitats, protected species, air and water pollution, municipal water and sewer systems, transportation systems, urban open space, community facilities, neighborhood character, and more. Impact assessments identify potentially undesirable outcomes, create opportunities for stakeholder input, and provide a legal framework for proposing mitigating measures. The scope of issues addressed and level of effort required to complete an impact assessment can vary dramatically depending on the size of the project and complexity of the issues involved.

In many locations, buildings must also comply with land use regulations called *zoning ordinances*. These govern the types of activities that may take place on a given piece of land, how much of the land may be covered by buildings, how far buildings must be set back from property lines, how many parking spaces must be provided, how large a total floor area may be constructed, and how tall the buildings may be. In larger cities, zoning ordinances may include fire zones with special fire-protection requirements, neighborhood enterprise districts with economic incentives for new construction or revitalization of existing buildings, or other special conditions.

Building Codes

Local governments also regulate building activity by means of *building codes*. Building codes protect public health and safety by setting minimum standards for construction quality, structural integrity, durability, livability, and especially fire safety.

Most building codes in North America are based on one of several *model codes*, standardized codes that local jurisdictions may adopt for their own use as a simpler alternative to writing their own. In Canada, the *National Building Code of Canada* is published by the Canadian Commission on Building and Fire Codes. It is the basis for most of that country's provincial and municipal building codes.

In the United States, the *International Building Code®* (*IBC*) is the predominant model code. This code is published by the International Code Council, a private, nonprofit organization whose membership consists of local code officials from throughout the country. It is the basis for most U.S. building codes enacted at the state, county, and municipal levels.

Building code–related information in this book is based on the IBC. The IBC begins by defining *occupancies* for buildings as follows:

- A-1 through A-5 Assembly: public theaters, auditoriums, lecture halls, nightclubs, restaurants, houses of worship, libraries, museums, sports arenas, and so on
- B Business: banks, administrative offices, college and university buildings, post offices, banks, professional offices, and the like
- E Educational: schools for grades K through 12 and some types of child day-care facilities
- F-1 and F-2 Factory Industrial: industrial processes using moderate-flammability and noncombustible materials, respectively
- H-1 through H-5 High Hazard: occupancies in which toxic, corrosive, highly flammable, or explosive materials are present
- I-1 through I-4 Institutional: occupancies in which occupants under the care of others may require assistance during a building emergency, such as 24-hour residential care facilities, hospitals, nursing homes, prisons, and some day-care facilities
- M Mercantile: stores, markets, service stations, salesrooms, and other retail and wholesale establishments
- R-1 through R-4 Residential: apartment buildings, dormitories, fraternity and sorority houses, hotels, one- and two-family dwellings, and assisted-living facilities
- S-1 and S-2 Storage: facilities for the storage of moderate- and low-hazard materials, respectively
- U Utility and Miscellaneous: agricultural buildings, carports, greenhouses, sheds, stables, fences, tanks, towers, and other secondary buildings

The IBC's purpose in describing occupancies is to identify different degrees of life-safety hazard in buildings. For example, a hospital, in which patients are bedridden and cannot escape a fire without assistance from others, must be designed to a higher standard of safety than a hotel or motel occupied by able-bodied residents. A large retail mall building, containing large quantities of combustible materials and occupied by many users varying in age and physical capacity, must be designed to a higher standard than a warehouse storing noncombustible materials and occupied by relatively few people who are all familiar with their surroundings. An elementary school requires more protection for its occupants than a university building. A theater, with patrons densely packed in dark spaces, requires more attention to emergency exits than does an ordinary office building.

These occupancy classifications are followed by a set of definitions for *construction types*. At the head of this list is Type I construction, made with highly fire-resistant, noncombustible materials. At the foot of it is Type V construction, which is built from combustible light wood framing—the least fire-resistant of all construction types. In between are Types II, III, and IV, with levels of resistance to fire falling between these two extremes.

With occupancies and construction types defined, the IBC proceeds to match the two, stating which occupancies may be housed in which types of construction, and under what limitations of building height and area. Figure 1.4 is a simplified summary of starting values in the IBC for maximum building height and area per floor for many combinations of occupancy and construction type. Once the values in this table are adjusted according to other provisions of the code, the

		Type of Construction								
		Type I		Type II		Type III		Type IV[a]	Type V	
		A	B	A	B	A	B	HT	A	B
Occupancy	Height[b]	U[e]	160	65	55	65	55	65	50	40
A-1	Stories[c]	U	5	3	2	3	2	3	2	1
	Area[d]	U	U	15,500	8,500	14,000	8,500	15,000	11,500	5,500
A-2	Stories	U	11	3	2	3	2	3	2	1
	Area	U	U	15,500	9,500	14,000	9,500	15,000	11,500	6,000
A-3	Stories	U	11	3	2	3	2	3	2	1
	Area	U	U	15,500	9,500	14,000	9,500	15,000	11,500	6,000
A-4	Stories	U	11	3	2	3	2	3	2	1
	Area	U	U	15,500	9,500	14,000	9,500	15,000	11,500	6,000
A-5	Stories	U	U	U	U	U	U	U	U	U
	Area	U	U	U	U	U	U	U	U	U
B	Stories	U	11	5	3	5	3	5	3	2
	Area	U	U	37,500	23,000	28,500	19,000	36,000	18,000	9,000
E	Stories	U	5	3	2	3	2	3	1	1
	Area	U	U	26,500	14,500	23,500	14,500	25,500	18,500	9,500
F-1	Stories	U	11	4	2	3	2	4	2	1
	Area	U	U	25,000	15,500	19,000	12,000	33,500	14,000	8,500
F-2	Stories	U	11	5	3	4	3	5	3	2
	Area	U	U	37,500	23,000	28,500	18,000	50,500	21,000	13,000
M	Stories	U	11	4	2	4	2	4	3	1
	Area	U	U	21,500	12,500	18,500	12,500	20,500	14,000	9,000
R-1	Stories	U	11	4	4	4	4	4	3	2
	Area	U	U	24,000	16,000	24,000	16,000	20,500	12,000	7,000
R-2	Stories	U	11	4	4	4	4	4	3	2
	Area	U	U	24,000	16,000	24,000	16,000	20,500	12,000	7,000
R-3	Stories	U	11	4	4	4	4	4	3	3
	Area	U	U	U	U	U	U	U	U	U
R-4	Stories	U	11	4	4	4	4	4	3	2
	Area	U	U	24,000	16,000	24,000	16,000	20,500	12,000	7,000
S-1	Stories	U	11	4	2	3	2	4	3	1
	Area	U	48,000	26,000	17,500	26,000	17,500	25,500	14,000	9,000
S-2	Stories	U	11	5	3	4	3	4	4	2
	Area	U	79,000	39,000	26,000	39,000	26,000	38,500	21,000	13,500

[a] See this figure's caption for information about new Type IV construction types to appear in the 2021 IBC.

[b] Height: Roof height above grade in feet (1ft = 0.3048 m).

[c] Stories: Number of stories above grade.

[d] Area: Area per floor in square feet (1 sq ft = 0.0920 m^2).

[e] U: Unlimited.

Figure 1.4

Simplified height and area limitations for common occupancies, from the 2018 IBC. In use, these values are further modified according to additional provisions to arrive at the final allowable height and area for any particular building. For the purposes of this book, many of these modifications are simplified or ignored. For information about new Type IV construction types related to tall mass timber buildings that will appear in the 2021 IBC, see Chapter 4.

maximum permitted size for a building of any particular use and type of construction can be determined.

Consider, for example, an office building. Under the IBC, this building is classified as Occupancy B, Business. Reading across the table from left to right, we find immediately that this building may be built to any desired height and area, without limit, using Type I-A construction.

Type I-A construction is defined in the IBC as consisting of only noncombustible structural materials—masonry, concrete, or steel, for example—and meeting certain requirements for resistance to the heat of fire. On the other hand, wood, being combustible, is (barring a few exceptions) not permitted for use in this construction type. Looking at the upper table in Figure 1.5, reproduced from the IBC, we find under Type I-A construction a listing of the required *fire resistance ratings*, measured in hours, for various parts of our proposed office building. For example, the first table row indicates that the structural frame, including such elements as columns, beams, and trusses, must be rated at 3 hours. The second row also mandates a 3-hour resistance for *bearing walls*, which serve to carry floors or roofs above. The third row indicates that exterior walls must also comply with the requirements of Table 602, which gives fire resistance rating requirements based on proximity to adjacent buildings or properties. (Table 602 is included in the lower portion of Figure 1.5.) Minimum requirements for interior *nonbearing walls and*

TABLE 601
FIRE-RESISTANCE RATING REQUIREMENTS FOR BUILDING ELEMENTS (HOURS)

BUILDING ELEMENT	TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
	A	B	A[d]	B	A[d]	B	HT	A[d]	B
Primary structural frame[g] (see Section 202)	3[a]	2[a]	1	0	1	0	HT	1	0
Bearing walls Exterior[f,g] Interior	 3 3[a]	 2 2[a]	 1 1	 0 0	 2 1	 2 0	 2 1/HT	 1 1	 0 0
Nonbearing walls and partitions Exterior	See Table 602								
Nonbearing walls and partitions Interior[e]	0	0	0	0	0	0	See Section 602.4.6	0	0
Floor construction and associated secondary members (see Section 202)	2	2	1	0	1	0	HT	1	0
Roof construction and associated secondary members (see Section 202)	1½[b]	1[b,c]	1[b,c]	0[c]	1[b,c]	0	HT	1[b,c]	0

TABLE 602
FIRE-RESISTANCE RATING REQUIREMENTS FOR EXTERIOR WALLS BASED ON FIRE SEPARATION DISTANCE[a, e, h]

FIRE SEPARATION DISTANCE = X (feet)	TYPE OF CONSTRUCTION	OCCUPANCY GROUP H[f]	OCCUPANCY GROUP F-1,M, S-1[g]	OCCUPANCY GROUP A, B, E, F-2, I, R, S-2[g], U[b]
X < 5[c]	All	3	2	1
5 ≤ X < 10	IA Others	3 2	2 1	1 1
10 ≤ X < 30	IA, IB IIB, VB Others	2 1 1	1 0 1	1[d] 0 1[d]
X ≥ 30	All	0	0	0

For SI: 1 foot = 304.8 mm.

FIGURE 1.5
Fire resistance of building elements, excerpted from the IBC. Types I and II construction restrict the building structure to noncombustible materials, that is, steel, concrete, and masonry. Type V construction allows any material, including wood. Types III and IV allow combinations of internal wood structure surrounded by noncombustible exterior walls. Additional provisions have been omitted for simplicity. For information about new Type IV construction types related to tall mass timber buildings that will appear in the 2021 IBC, see Chapter 4.

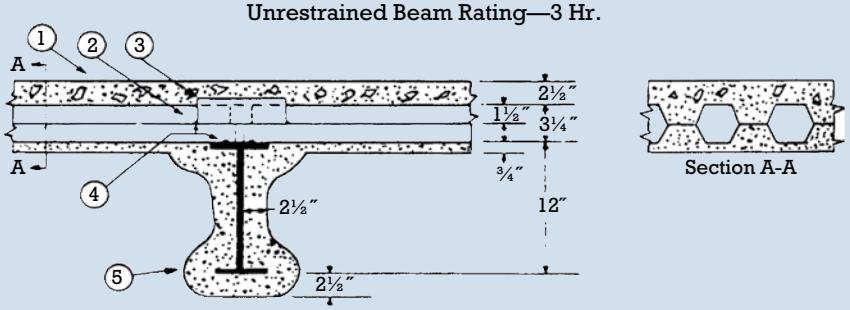
(Tables 601 and 602 excerpted from the 2012 International Building Code, Copyright 2011. Washington, DC: International Code Council. Reproduced with permission. All rights reserved. www.ICCSAFE.org)

partitions, which carry no loads from above, and for floor and roof construction are defined in the other rows of the table.

Taking a closer look at Tables 601 and 602 in Figure 1.5, we see that Type I-A construction is the least vulnerable to fire: It is constructed of noncombustible structural materials and with the highest fire resistance ratings. Reading across the table, we see other construction types, some with lesser fire resistance ratings and some with fewer restrictions on the use of combustible materials. At the far right of the table, we find Type V-B construction, in which any structural material is permitted, both noncombustible and combustible, and no fire protection is required. These differences are reflected in Figure 1.4, in which the least vulnerable construction type, Type I-A, is permitted the greatest height and area, and other increasingly vulnerable types are limited to progressively lesser heights and areas.

Once fire resistance rating requirements for the major parts of a building have been determined, the design of these parts can proceed, using building assemblies meeting these requirements. Tabulated fire resistance ratings for building materials and assemblies come from a variety of sources, including the IBC itself, as well as from catalogs and handbooks issued by building material manufacturers, construction trade associations, and organizations concerned with fire protection of buildings. In each case, the ratings are derived from large-scale laboratory tests carried out in accordance with an accepted standard protocol to ensure uniformity of results. (The most important of such tests, ASTM E119, is described more fully in Chapter 22

Design No. A814
Restrained Assembly Rating—3 Hr.
Unrestrained Assembly Rating—3 Hr.
Unrestrained Beam Rating—3 Hr.



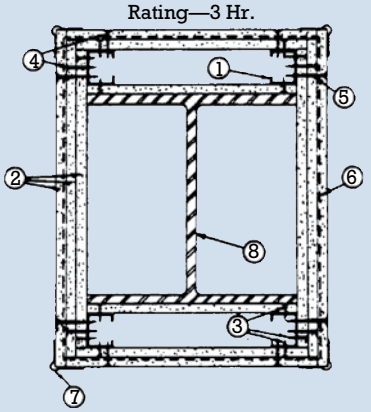
Beam—W 12 × 27, min size.
1. **Sand-Gravel Concrete**—150 pcf unit weight 4000 pcf compressive strength.
2. **Steel Floor and Form Units***—Non-composite 3 in. deep galv units. All 24 in. wide, 18/18 MSG min cellular units. Welded to supports 12 in. O.C. Adjacent units button-punched or welded 36 in. O.C. at joints.
3. **Cover Plate—**No. 16 MSG galv steel.
4. **Welds—**12 in. O.C.
5. **Fiber Sprayed***—Applied to wetted steel surfaces which are free of dirt, oil or loose scale by spraying with water to the final thickness shown above. The use of adhesive and sealer and the tamping of fiber are optional. The min and density of the finished fiber should be 11 pcf and the specified fiber thicknesses require a min fiber density of 11 pcf. For areas where the fiber density is between 8 and 11 pcf, the fiber thickness shall be increased in accordance with the following formula:

$$\text{Thickness, in.} = \frac{(11)\ (\text{Design Thickness, in.})}{\text{Actual Fiber Density, pcf.}},$$

Fiber density shall not be less than 8 pcf. For method of density determination refer to General Information Section.

*Bearing the UL Classification Marking.

Design No. ×511
Rating—3 Hr.



1. **Steel Studs**—1⅝ in. wide with leg dimensions of 1-5/16 and 1-7/16 in. with a ¼-in. folded flange in legs, fabricated from 25 MSG galv steel, ¾- by 1¾-in. rectangular cutouts punched 8 and 16 in. from the ends. Steel stud cut ⅛ in. less in length than assembly height.
2. **Wallboard, Gypsum***—½ in. thick, three layers.
3. **Screws**—1 in. long, self-drilling, self-tapping steel screws, spaced vertically 24 in. O.C.
4. **Screws**—1⅝ in. long, self-drilling, self-tapping steel screws, spaced vertically 24 in. O.C., except on the outer layer of wallboard on the flange, which are spaced 12 in. O.C.
5. **Screws**—2¼ in. long, self-drilling, self-tapping steel screws, spaced vertically 12 in. O.C.
6. **Tie Wire**—One strand of 18 SWG soft steel wire placed at the upper one-third point, used to secure the second layers of wallboard only.
7. **Corner Beads**—No. 28 MSG galv steel, 1¼ in. legs or 27 MSG uncoated steel, 1⅜ in. legs,

FIGURE 1.6
Fire resistance ratings for a steel floor structure (*top*) and column (*bottom*), taken from the Underwriters Laboratories' *Fire Resistance Directory*. In the floor assembly, the terms "restrained" and "unrestrained" refer to whether or not the floor is connected to its supporting structure in such a way that it is, or is not, prevented from expanding longitudinally when subjected to the heat of a fire.
(Reprinted with permission of Underwriters Laboratories Inc.)

of this book.) Figure 1.6 shows examples of how such ratings are commonly presented.

In general, when determining the level of fire resistance required for a building, the greater the degree of fire resistance, the higher the cost. Most frequently, therefore, buildings are designed to the lowest level of resistance permitted by the building code. Our hypothetical office building could be built using Type I-A construction, but does it really have to be constructed to this high standard?

Let us suppose that the owner desires a three-story building with 30,000 square feet per floor. Reading across the table in Figure 1.4, we can see that in addition to Type I-A construction, the building can be of Type I-B construction, which permits a building of 11 stories and unlimited floor area; or of Type II-A construction, which permits a building of 5 stories and 37,500 square feet per floor. But it cannot be of Type II-B construction, which allows a building of only three stories and 23,000 square feet per floor. It can also be built of Type IV-HT construction but not of Type III or Type V.

Other factors also come into play in these determinations. If a building is protected throughout by a fully automatic sprinkler system for suppression of fire, the tabulated area per floor may, in many cases, be tripled for a multistory building or quadrupled for a single-story building. The rationale for this permitted increase is the added safety to life and property provided by such a system. A one-story increase in allowable height is also granted under most circumstances if such a sprinkler system is installed. If the three-story, 30,000-square-foot office building that we have been considering is provided with such a sprinkler system, a bit of arithmetic will show that it can be built of any construction type shown in Figure 1.4 except Type V.

If more than a quarter of the building's perimeter walls face public ways or open spaces accessible to fire-fighting equipment, an additional increase of up to 75 percent in allowable area is granted in accordance with another formula. Furthermore, if a building is divided by fire walls having the fire resistance ratings specified in another table (Figure 1.7), each divided portion may be considered a separate building for purposes of computing its allowable area, which effectively permits the creation of a building many times larger than Figure 1.4 would, at first glance, indicate. (For the sake of simplicity, additional considerations in determining the allowable building height and area in the IBC have been omitted from these examples.)

The IBC also establishes standards for natural light; ventilation; *means of egress* (exiting during building emergencies); structural design; construction of floors, walls, and ceilings; chimney construction; fire-protection systems; accessibility for disabled persons; and many other important aspects of building design. In addition to the IBC, the International Code Council also publishes the *International Residential Code for One- and Two-Family Dwellings* (*IRC*), a simplified model code addressing the construction of detached one- and two-family homes and townhouses of limited size. Within any particular building agency, these codes may be adopted directly in their model form. Or, as is more common, they may be adopted with amendments, adjusting the code to suit the needs of that jurisdiction while still retaining its overall structure and intent.

The building code is not the only code with which a new building must comply. Energy codes establish standards of energy efficiency for buildings, affecting a designer's choices of windows, heating and cooling systems, and many aspects of the construction of a building's enclosing walls and roofs. Because of the significant environmental impacts associated with building energy consumption, the development of more stringent energy codes that require buildings to consume less energy is one of the important contributors to improving building sustainability.

Health codes regulate aspects of design and operation related to sanitation in public facilities such as swimming pools, food-service operations, schools, or healthcare facilities. Fire codes regulate the operation and maintenance of buildings to ensure that egress pathways, fire-protection systems, emergency power, and other

TABLE 706.4
FIRE WALL FIRE-RESISTANCE RATINGS

GROUP	FIRE-RESISTANCE RATING (hours)
A, B, E, H-4, I, R-1, R-2, U	3[a]
F-1, H-3[b], H-5, M, S-1	3
H-1, H-2	4[b]
F-2, S-2, R-3, R-4	2

a. In Type II or V construction, walls shall be permitted to have a 2-hour fire-resistance rating.
b. For Group H-1, H-2 or H-3 buildings, also see Sections 415.6 and 415.7.

FIGURE 1.7
Fire resistance requirements for fire walls, according to the IBC. For more information about fire walls, see Chapter 23. *(Table 706.4 excerpted from the 2012 International Building Code, Copyright 2011. Washington, DC: International Code Council. Reproduced with permission. All rights reserved. www.ICCSAFE.org)*

life-safety systems are properly maintained. Electrical and mechanical codes regulate the design and installation of building electrical, plumbing, and heating and cooling systems. Some of these codes may be locally written, but, like the building codes discussed earlier, most are based on national models. In fact, an important task in the early design of any major building is determining what agencies have jurisdiction over the project and what codes and regulations apply.

Other Constraints

Other types of legal restrictions must also be observed in the design and construction of buildings. Along with the accessibility provisions of the IBC, the *Americans with Disabilities Act* (*ADA*) makes accessibility to public buildings a civil right of all Americans, and the *Fair Housing Act* does the same for much multifamily housing. Together, these *equal access standards* regulate the design of entrances, stairs, doorways, elevators, toilet facilities, public areas, living spaces, and other parts of many buildings to ensure that they are usable by members of the population with special access needs. The U.S. *Occupational Safety and Health Administration* (*OSHA*) controls the design of workplaces to minimize hazards to the health and safety of workers. OSHA sets safety standards under which a building must be constructed and also has an important role in the design of industrial and commercial buildings.

Fire insurance companies exert a major influence on construction standards. Through their testing and certification organizations (Underwriters Laboratories and Factory Mutual, for example) and the rates they charge for building-insurance coverage, these companies offer financial incentives to building owners to build hazard-resistant construction. Federal labor agencies, building contractor associations, and construction labor unions have standards, both formal and informal, that affect the ways in which buildings are built. Contractors have particular types of equipment, certain kinds of skills, and customary ways of going about things. All of these affect a building design in myriad ways and must be appropriately considered by building designers.

Construction Standards and Information Resources

The tasks of the architect and the engineer would be much more difficult to carry out without the support of dozens of standards-setting agencies, trade associations, professional organizations, and other groups that produce and disseminate information on materials and methods of construction, some of the most important of which are discussed in the following sections.

Standards-Setting Agencies

ASTM International is a private organization that establishes specifications for materials and methods of construction accepted as standards throughout the United States. Numerical references to ASTM standards—for example, ASTM C150 for portland cement, used in making concrete—are found throughout building codes and construction specifications, where they are used as a precise shorthand for describing the quality of materials or the requirements of their installation. Throughout this book, references to ASTM standards are provided for the major building materials presented. In Canada, corresponding standards are set by the *Canadian Standards Association* (*CSA*). The *International Organization for Standardization* (*ISO*), an organization with more than 160 member countries, performs a similar role internationally.

The *American National Standards Institute* (*ANSI*) is another private organization that certifies North American standards for a broad range of products, such as exterior windows and mechanical components of buildings. Government agencies, most notably the U.S. Department of Commerce's *National Institute of Science and Technology* (*NIST*) and the National Research Council Canada's *Institute for Research in Construction* (*NRC-IRC*), also sponsor research and establish standards for building products and systems.

Construction Trade and Professional Associations

Design professionals, building materials manufacturers, and construction trade groups have formed a large number of organizations that work to develop technical standards and disseminate information related to their respective fields of interest. The Construction Specifications Institute, whose MasterFormat™ standard is described in the following section, is one example. This organization is composed both of independent building professionals, such as architects and engineers, and of industry members. The Western Wood Products Association, to choose an example from among hundreds of *trade associations*, is made up of producers of lumber and wood products. It carries out research programs on wood products, establishes uniform standards of product quality, certifies mills and products that conform to its standards, and publishes authoritative technical literature concerning the use of lumber and related products. Associations with a similar range of activities exist for virtually every material and product used in building. All of them publish technical data relating to their fields of interest, and many of these publications are indispensable references for the architect or engineer. In some cases, the standards published by these organizations are even incorporated by reference into the building codes, making them, in effect, legal requirements. Selected publications from professional and trade associations are identified in the references listed at the end of each chapter in this book. The reader is encouraged to obtain

and explore these publications and others available from these various organizations.

MasterFormat and Other Systems of Organizing Building Information

The *Construction Specifications Institute* (*CSI*) of the United States, and its Canadian counterpart, *Construction Specifications Canada* (*CSC*), have evolved over a period of many years a comprehensive outline called *MasterFormat* for organizing information about construction materials and systems. This format is used for the written construction specifications for the vast majority of large building construction projects in these two countries. It is frequently used to organize construction cost data, and it forms the basis on which most trade associations' and manufacturers' technical literature is cataloged. In some cases, MasterFormat is used to cross-reference materials information on construction drawings as well.

MasterFormat is organized into 50 primary *specification divisions* intended to cover the broadest possible range of construction materials and buildings systems. The portions of MasterFormat relevant to the types of construction discussed in this book are as follows:

Procurement and Contracting Requirements Group
- Division 00—Procurement and Contracting Requirements

Specifications Group

General Requirements Subgroup
- Division 01—General Requirements

Facility Construction Subgroup
- Division 02—Existing Conditions
- Division 03—Concrete
- Division 04—Masonry
- Division 05—Metals
- Division 06—Wood, Plastics, and Composites
- Division 07—Thermal and Moisture Protection
- Division 08—Openings
- Division 09—Finishes
- Division 10—Specialties
- Division 11—Equipment
- Division 12—Furnishings
- Division 13—Special Construction
- Division 14—Conveying Equipment

Facilities Services Subgroup
- Division 21—Fire Suppression
- Division 22—Plumbing
- Division 23—Heating, Ventilating, and Air Conditioning (HVAC)
- Division 25—Integrated Automation
- Division 26—Electrical
- Division 27—Communications
- Division 28—Electronic Safety and Security

Site and Infrastructure Subgroup
- Division 31—Earthwork
- Division 32—Exterior Improvements
- Division 33—Utilities

These broadly defined divisions are further subdivided into *sections*, each describing a discrete scope of work often provided by a single construction trade or subcontractor. Individual sections are identified by six-digit codes, in which the first two digits correspond to the division number and the remaining four digits identify subcategories and individual units within the division. Within Division 05—Metals, for example, some commonly referenced sections are:

- Section 05 12 00—Structural Steel Framing
- Section 05 21 00—Steel Joist Framing
- Section 05 31 00—Steel Decking
- Section 05 40 00—Cold-Formed Metal Framing
- Section 05 50 00—Metal Fabrications

Every chapter in this book gives MasterFormat designations for the information it presents to help familiarize the reader with this system, and to provide guidance on where to look in construction specifications and other technical resources for further information.

MasterFormat organizes building systems information primarily according to work product, that is, the work of discrete building trades. This makes it especially well suited for use during the construction phase of building. For example, Section 06 10 00—Rough Carpentry specifies the materials and work of rough carpenters who erect a wood light frame building structure. However, finish carpentry, such as the installation of interior doors and trim, occurs later during construction, requires different materials, and is performed by different workers with different skills and tools. So it is specified separately in Section 06 20 00—Finish Carpentry. Defining each of these aspects of the work separately allows the architect to describe the work accurately and the contractor to efficiently manage the work's execution.

The *UniFormat*™ standard organizes building systems information into functional groupings. For example, UniFormat defines eight Level 1 categories:

- A Substructure
- B Shell
- C Interiors
- D Services
- E Equipment and Furnishings
- F Special Construction and Demolition
- G Building Sitework
- Z General

Where greater definition is required, these categories are subdivided into so-called Level 2 classes,

Level 3 and 4 subclasses, and even Level 5 or higher-numbered sub-subclasses, each describing more finely divided aspects of a system or assembly. For example, wood floor joist framing can fall under any of the following UniFormat descriptions:

- Level 1: B Shell
- Level 2: B10 Superstructure
- Level 3: B1010 Floor Construction
- Level 4: B1010.10 Floor Structural Frame
- Level 5: B1010.10.WF Wood Floor Framing
- Etc.

UniFormat provides a more systems-based view of construction in comparison to MasterFormat and is most useful where a broader, more flexible description of building information is needed. This includes, for example, description of building systems and assemblies during project definition and early design, or the performance specification of building systems, such as discussed later in this chapter for design/build project delivery. UniFormat is also well suited to organizing construction data in computer-aided design and building information modeling systems, which naturally tend to aggregate information into functional groupings. (Building information modeling is discussed at greater length later in this chapter.)

The *OmniClass™ Construction Classification System* is an overarching scheme that attempts to incorporate multiple existing building information organizational systems, including MasterFormat, UniFormat, and others, into one system. OmniClass consists of 15 *Tables*, some of which include:

- Table 13: Spaces by Function
- Table 21: Elements
- Table 22: Work Results
- Table 23: Products
- Table 31: Phases
- Table 32: Services
- Table 35: Tools
- Table 41: Materials
- Table 49: Properties

For example, Table 13—Spaces by Function merges a number of existing systems for the management of information about rooms and spaces within buildings, useful to building owners and facilities managers. Table 21—Elements is based on UniFormat, and Table 22—Work Results is based on MasterFormat. OmniClass is an open standard that is described broadly by its authors as "a strategy for classifying the built environment." It is based on an international standard for organizing construction information, ISO 120006-2, and it continues to undergo active development.

The increasing attention given to organizational systems like UniFormat and OmniClass reflects the building industry's need to manage increasingly complex sets of data and efficiently share that data between disciplines, across diverse information technology platforms, and throughout the full building life cycle, from conception to extended occupancy.

The Work of the Construction Professional

Providing Construction Services

An owner wishing to construct a building hopes to achieve a finished project that functions as intended, meets expectations for quality, costs as little as possible, and is completed on a predictable schedule. A contractor offering its construction services hopes to produce quality building, earn a profit, and complete the project in a timely fashion. Yet, the process of building itself is fraught with uncertainty: It is subject to the vagaries of the labor market, commodity prices, and the weather; despite the best planning efforts, unanticipated conditions arise, delays occur, and mistakes are made; not infrequently, requirements change over the course of the project; and the pressures of schedule and cost inevitably minimize the margin for miscalculation. In this high-stakes environment, the relationship between the owner and contractor must be structured to share reasonably between them the potential rewards and risks.

Construction Project Delivery Methods

In traditional *design/bid/build* project delivery (Figure 1.8, *left*), the owner first hires a team of architects and engineers to perform design services, leading to the creation of construction documents that comprehensively describe the facility to be built. Next, construction firms are invited to bid on the project. Each bidding firm reviews the construction documents and proposes a cost to construct the facility. The owner evaluates the submitted proposals and awards the construction contract to the bidder deemed most suitable. This selection may be based on bid price alone, or other factors related to bidders' qualifications may also be considered. The construction documents then become part of the construction contract, and the selected firm proceeds with the work. On all but small projects, this firm acts as the *general contractor*, coordinating and overseeing the construction process but frequently relying on smaller, more specialized *subcontractors* to perform significant portions or even all of the work itself. During construction, the design team continues to provide services to the owner, helping to ensure that the facility is built according to the requirements of the documents as well as answering questions related to the design, changes to the work, verification of payments to the contractor, and similar matters.

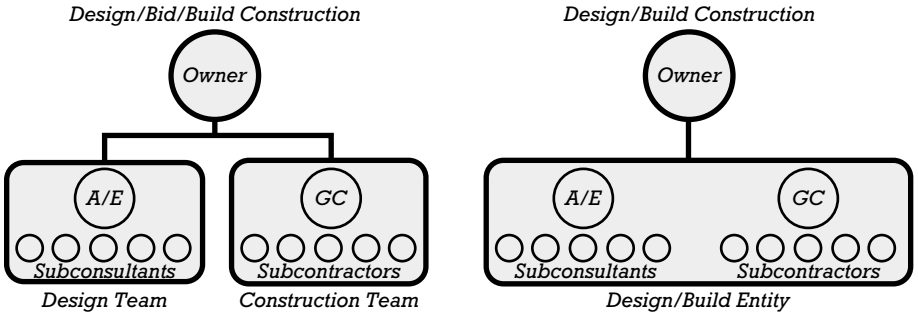


FIGURE 1.8
In design/bid/build project delivery (*left*), the owner contracts separately with the architect/engineer (A/E) design team and the construction general contractor (GC). In a design/build project (*right*), the owner contracts with a single organizational entity that provides both design and construction services.

Among the advantages of design/bid/build project delivery are its easy-to-understand organizational scheme, well-established legal precedents, and relative simplicity of management. The direct relationship between the owner and the design team ensures that the owner retains control over the design and provides a healthy set of checks and balances during the construction process. With design work completed before the project is bid, the owner starts construction with a well-defined scope of work and a high degree of confidence regarding the construction schedule and costs.

In design/bid/build project delivery, the owner contracts with two entities, and design and construction responsibilities remain divided between these two throughout the project. In *design/build* project delivery, one entity assumes responsibility for both design and construction (Figure 1.8, *right*). A design/build project begins with the owner developing a conceptual design or program that describes the functional or performance requirements of the proposed facility but does not detail its form or how it is to be constructed. Next, using this conceptual information, a design/build organization is selected to complete the design and construction of the project. Selection of the designer/builder may be based on a competitive bid process similar to that for design/bid/build projects, on negotiation and evaluation of an organization's qualifications for the proposed work, or on some combination of these. Design/build organizations themselves can take a variety of forms: a single firm encompassing both design and construction expertise; a construction management firm that subcontracts with a separate design firm to provide those services; or a joint venture between two firms, one specializing in construction and the other in design. Regardless of the internal structure of the design/build organization, the owner contracts with this single entity throughout the remainder of the project, and this entity assumes responsibility for all design and construction services.

Design/build project delivery gives the owner a single source of accountability for all aspects of the project. It also places the designers and constructors in a closer working relationship, introducing construction expertise into the design phases of a project and allowing the earliest possible consideration of constructability, cost control, construction scheduling, and similar matters. This delivery method also readily accommodates fast track construction, a scheduling technique for reducing construction time that is described later in this chapter.

Other delivery methods are possible: An owner may contract separately with a design team and a *construction manager* (*CM*) (Figure 1.9). As in design/build construction, the construction manager participates in the project prior to the onset of construction, introducing construction expertise during the design stage. Construction management project

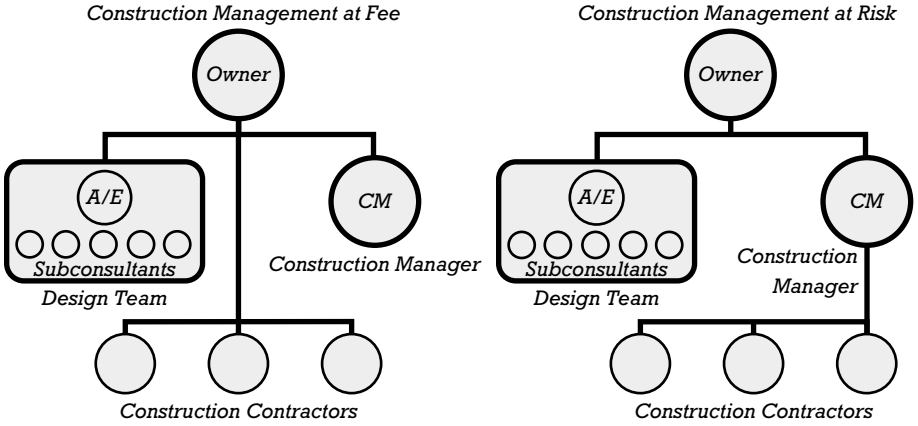


FIGURE 1.9
In its traditional role, a construction manager (CM) at fee (*left*) provides project management services to the owner and assists the owner in contracting directly for construction services with one or more construction entities. A CM at fee is not directly responsible for the construction work itself. A CM at risk (*right*) acts more like a general contractor and takes on greater responsibility for construction quality, schedule, and costs. In either case, the A/E design team also contracts separately with the owner.

delivery can take a variety of forms and is frequently associated with especially large or complex projects. In *turnkey* construction, an owner contracts with a single entity that provides not only design and construction services, but financing for the project as well. Or design and construction can be undertaken by a *single-purpose entity*, of which the owner, architect, and contractor are all joint members. Aspects of these and other project delivery methods can also be intermixed, allowing many possible organizational schemes for the delivery of design and construction services that are suitable to a variety of owner requirements and project circumstances.

Paying for Construction Services

With *fixed-fee*, or *lump-sum*, compensation, the general contractor or other construction entity is paid a fixed dollar amount to complete the construction of a project regardless of that entity's actual costs to perform the work. With this compensation method, the owner begins construction with a known, fixed cost and assumes minimal risk for unanticipated cost increases. In contrast, the construction contractor assumes most of the risk of unforeseen costs, but also stands to gain from potential savings. Fixed-fee compensation is most suitable to projects where the scope of the construction work is well defined when the construction fee is set, as is the case, for example, with design/bid/build construction.

With *cost plus a fee* compensation, the owner agrees to pay the construction entity for the actual costs of construction—whatever they may turn out to be—plus an additional amount to account for overhead and profit. In this case, the construction contractor is shielded from most cost uncertainty, and it is the owner who assumes most of the risk of added costs and stands to gain the most from potential savings. Cost plus a fee compensation is most often used with projects for which the scope of construction work is not fully known at the time compensation is established, a circumstance most frequently associated with construction management or design/build contracts.

Cost plus a fee compensation may also include a *guaranteed maximum price* (*GMAX* or *GMP*). In this case, there is a maximum fee that the owner may be required to pay. While the contractor's compensation remains under the guaranteed amount, compensation is made in the same manner as with a standard cost plus a fee contract. However, once the compensation reaches the guaranteed maximum, the owner is no longer required to make additional payments and the contractor assumes responsibility for all additional costs. This compensation method retains some of the scope and price flexibility of cost plus a fee compensation while also establishing a limit on the owner's cost risk.

Incentive provisions in owner/contractor agreements can be used to more closely align owner and contractor interests. For example, in simple cost plus a fee construction, there may be an incentive for a contractor to add costs to a project, as these added costs will generate added fees. To eliminate such a counterproductive incentive, a bonus fee or profit-sharing provision can provide for some portion of construction cost savings to be returned to the contractor. In this way, the contractor and owner jointly share in the benefits of reduced construction cost. Bonuses and penalties for savings or overruns in costs and schedules can be part of any type of construction contract.

Surety bonds are another form of legal instrument used to manage financial risks of construction, most frequently with publicly financed or very large projects. The purpose of a surety bond is to protect an owner from the risks of default, such as bankruptcy, by the construction contractor. For a fixed fee, a third party (surety) promises to complete the contractual obligations of the contractor if that contractor should for any reason fail to do so. Most commonly, two separate bonds are issued, one for each of the general contractor's principal obligations: a *performance bond* to assure completion of the construction and a *payment bond* to assure full payment to suppliers and subcontractors.

With competitive bidding and fixed-fee compensation, the owner is assured of competitive pricing for construction services and the contractor assumes most of the risk for unanticipated costs. With a negotiated contract and simple cost plus a fee compensation, the risks of noncompetitive pricing and unanticipated costs are shifted more toward to the owner. By adjusting project delivery and compensation methods, these and other construction-related risks can be allocated in varying degrees between the two parties to best suit the requirements of any particular project.

Sequential versus Fast Track Construction

In *sequential construction* (Figure 1.10), each major phase in the design and construction of a building is completed before the next phase begins, and construction does not start until all design work has been completed. Sequential construction can take place under any of the project delivery methods described previously. It is frequently associated with design/bid/build construction, where the separation of design and construction phases fits naturally with the contractual separation between design and construction service providers.

Phased construction, also called *fast track construction*, aims to reduce the time required to complete a project by overlapping the design and construction of various project parts (Figure 1.10). By allowing construction to start sooner and by

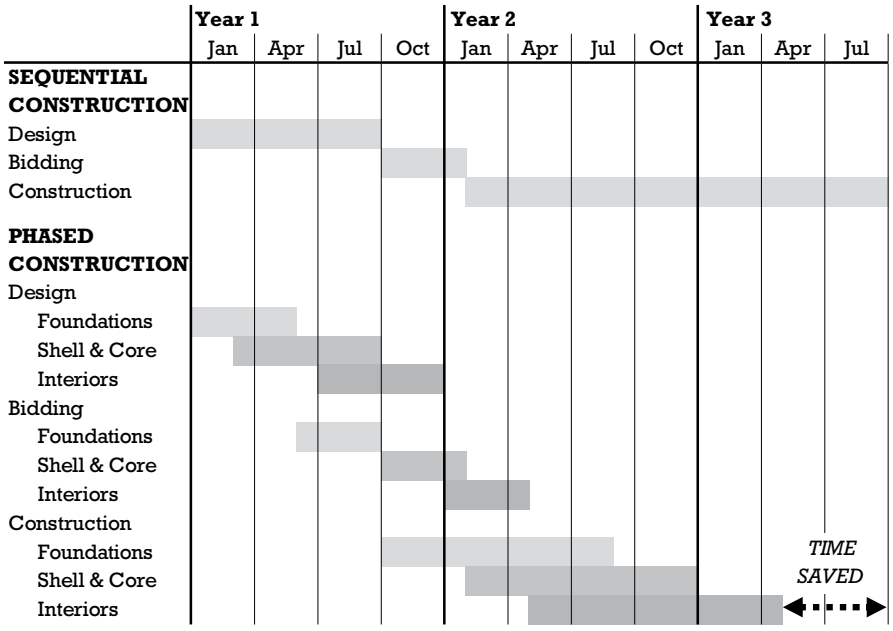


FIGURE 1.10

In sequential construction, construction does not begin until design is complete. In phased construction, design and construction activities overlap, with the goal of reducing the overall time required to complete a project.

overlapping the work of design and construction, phased construction can reduce the total time required to complete a project. However, phased construction also introduces its own risks. Because construction on some parts of the project begins before all design is complete, an overall cost for the project cannot be established until a significant portion of construction is underway. Phased construction also introduces more complexity into the design process and increases the potential for design errors (for example, if foundation design does not adequately anticipate the requirements of the not yet fully engineered structure above). Phased construction can be applied to any construction delivery method discussed earlier. It is frequently associated with design/build and construction management project delivery methods, where the early participation of the construction entity provides resources that are helpful in managing the coordination of overlapping design and construction activities.

Construction Scheduling

Constructing a building of any significant size is a complex endeavor, requiring the combined efforts of countless participants and the coordination of myriad tasks. Managing this process requires an in-depth understanding of the work required, of the ways in which different aspects of the work depend upon each other, and of the constraints on the sequence in which the work must be performed.

Figure 1.11 captures one moment in the construction of a tall building. The process is led by the construction of the building's central, stabilizing core structures (in the photograph, the pair of concrete tower-like structures extending above the highest floor levels). This work is followed by construction of the surrounding floor structures, which rely, in part, on the previously completed cores for support. Attachment of the exterior skin can follow only after the floor plates are securely in place. As the building skin is installed and floor areas become protected from the weather, further operations, such as the roughing in of mechanical and electrical systems, and eventually, the installation of finishes and other elements, can proceed in turn. This simple example illustrates considerations that apply to virtually every aspect of building construction and at every scale from a building's largest systems to its smallest details: Successful construction requires a detailed understanding of the tasks required and their interdependencies in time and space.

The construction project schedule is used to analyze and represent

FIGURE 1.11

In this photo, the construction sequence of a tall building is readily apparent: A pair of concrete core structures leads the construction, followed by concrete columns and floor plates and, finally, the enclosing curtain wall. *(Photo by Joseph Iano.)*

construction tasks, their relationships, and the sequence in which they must be performed. Development of the schedule is a fundamental part of construction project planning, and regular updating of the schedule throughout the life of the project is essential to its successful management. In a *Gantt* (or *bar*) *chart*, a series of horizontal bars represents the duration of various tasks or groups of tasks that make up the project. Gantt charts provide an easy-to-understand representation of construction tasks and their relationships in time. They can be used to provide an overall picture of a project schedule, with only a project's major phases represented (Figure 1.10), or they can be expanded to represent a larger number of more narrowly defined tasks at greater levels of project detail (Figure 1.12).

The *critical path* of a project is the sequence of activities that determines the least amount of time in which a project can be completed. For example, the construction of a building's primary structural system is commonly on the critical path of a project schedule. If any of the activities on which the completion of this system depends—such as design, shop drawing production and review, component fabrication, materials delivery, or erection on site—are delayed, then the final completion date of the project will be extended. In contrast, other systems not on the critical path have more flexibility in their scheduling, called *float*, and delays (within limits) in their execution will not necessarily affect the overall project schedule.

The *critical path method* (*CPM*) is a technique for analyzing collections of activities and optimizing the project schedule to minimize the duration and cost of a project. This requires a detailed breakdown of the work involved in a project and the identification of dependencies among the parts (Figure 1.13). This information is combined with considerations of cost and resources available to perform the work, and then analyzed, usually with the assistance of computer software, to identify optimal scenarios for scheduling and worker and resource allocation. Once the critical path of a project has been established, the elements on this path are likely to receive a high degree of scrutiny during the life of the project, as delays in any of these steps will have a direct impact on the overall project schedule.

Projects of different sizes and degrees of complexity, and even

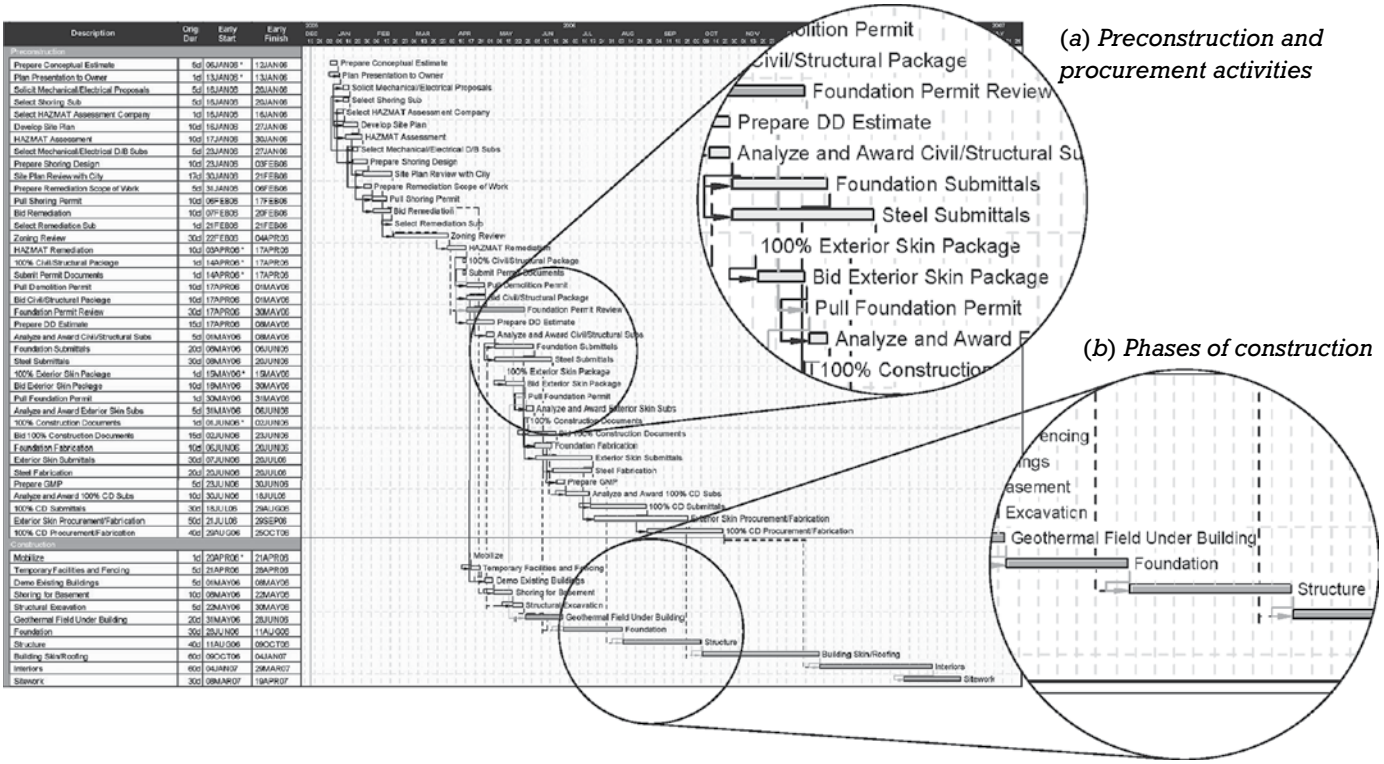


FIGURE 1.12

In a Gantt chart, varying levels of detail can be represented. In this example, roughly the top three-quarters of the chart is devoted to a breakdown of preconstruction and procurement activities, such as bidding portions of the work to subtrades, preparing cost estimates, and making submittals to the architect (*a*). Construction activities, represented more broadly, appear in the bottom portion (*b*).

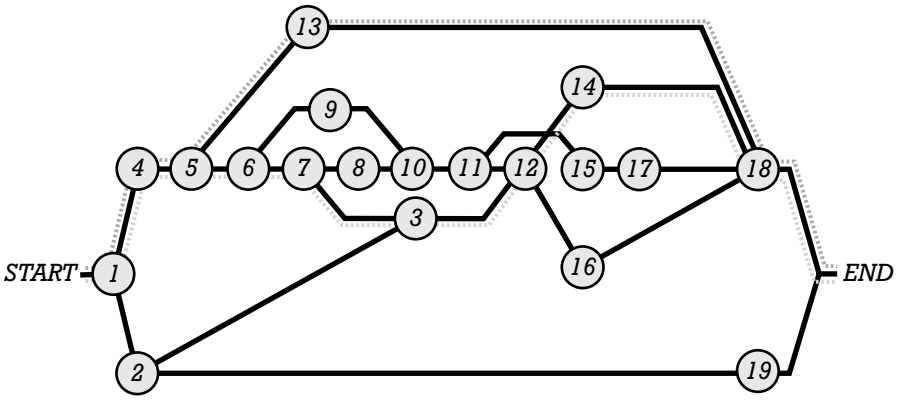


FIGURE 1.13

The critical path method depends on a detailed analysis of work tasks and their relationships to generate an optimal construction schedule. Shown here is a schematic network diagram representing task dependencies. For example, task 6 cannot begin until tasks 1, 4, and 5 are completed, and tasks 7 and 9 cannot begin until task 6 is finished. The dashed lines on the diagram trace two of many possible paths from the start to the end of the diagram. To determine the critical path for this collection of tasks, all such paths must be identified and the time required to complete each one calculated. The path requiring the most time to complete is the critical path, that is, the sequence of activities that determines the least time in which the collection of tasks as a whole can be completed.

different phases of planning and work within a single project, require schedules that differ in their degree of definition and level of detail. AACE International, an organization dedicated to promoting effective cost management practices, provides a useful system for defining different types of constructions schedules. The degree of project definition in a schedule is described by five *schedule classes*. For example, a Class 5 schedule provides the least project definition and is appropriate to early conceptual work. A Class 3 schedule relies on a medium degree of definition and is suitable, for example, to project budgeting during design phases. A Class 1 schedule provides the highest degree of project definition, such as that needed for project bidding and costing.

Similarly, *schedule levels* define the amount of detail provided within the construction schedule. For example, a Level 1 schedule may be represented as a simple Gantt chart, outlining major project components and their duration. This type of schedule is appropriate for high-level description of a project overall, but is not sufficient for monitoring and controlling project processes. A Level 3 schedule, such as a comprehensive CPM schedule, provides much more detail and can perform as an effective project management tool. Level 4 schedules provide an even finer degree of detail and are used to describe segments of an overall schedule. *Rolling* (or *look-ahead*) *schedules,* in which day-to-day processes extending a limited number of weeks or months into the future are described, are examples of Level 4 schedules.

Managing Construction

Once a construction project is underway, the general contractor assumes responsibility for day-to-day oversight of the construction site, management of trades and suppliers, and communications between the construction team and other major parties, such as the owner and the architect. On projects of any significant size, this may include responsibility for filing construction permits, securing the project site, providing temporary power and water, setting up office trailers and other support facilities, providing insurance coverage for the work in progress, managing personnel on site, maintaining a safe work environment, stockpiling materials, performing testing and quality control, providing site surveying and engineering, arranging for cranes and other construction machinery, providing temporary structures and weather protection, disposing or recycling of construction waste, soliciting the work of subtrades and coordinating their efforts, submitting product samples and technical information to the design team for review, maintaining accurate records of the construction as it proceeds, monitoring costs and schedules, managing changes to the work, protecting completed work, and more.

Trends in the Delivery of Design and Construction Services

Fostering Collaboration

The design and construction industry continues to test innovative organizational structures and project delivery methods in which designers, builders, and owners assume less adversarial and less compartmentalized roles. Such approaches share characteristics such as:

- Contractual relationships and working arrangements that foster collaboration between primary project participants—the designer, owner, and builder
- Early involvement of all parties, including participation of the construction entity during the design phases of a project
- Shared risk and reward

• Expanded project services to more fully address the full life of a project—from its original conception through planning, design, and construction to postconstruction occupancy—to best serve the needs of the building owner

The growth of design/build in the construction marketplace is one example of this trend: Between 1980 and the present, the share of private, nonresidential construction work performed as design/build construction has increased from roughly 5 percent of the total market to 45 percent.

The current state of the art in collaborative project delivery is *integrated project delivery* (*IPD*). In IPD, the major parties—including at least the design team, construction team, and owner group—share mutually the responsibilities, decision-making, and financial risks and rewards of the project. In its purest form, the parties share one agreement, for example, as a single-purpose entity, binding them all to the same goals and outcomes. In other cases, a shared joining agreement may be used to mutually bind parties contracted under separate agreements. The goal of IPD and similar efforts is to increase efficiency, improve project outcomes, and reduce conflict and litigation.

Improving Productivity

Industry efforts also focus on improvements in the efficiency of construction processes themselves. For example, a typical single-family home may be made of more than 100,000 separate pieces, assembled by as many as 1,000 workers. Estimates of inefficiency in the general construction market sector range as high as 50 percent or more, equating, in the U.S. market, to $400 to $600 billion wasted annually. And while U.S. nonfarm productivity has more than doubled since 1964, productivity in the construction sector has remained unchanged or even declined during the same period.

Unlike factory production, most building construction takes place outdoors, is performed within physically challenging work areas, and is executed by a highly fragmented workforce. Despite the differences in production environments, the construction industry is drawing lessons from factory production to improve its own processes. Sometimes called *lean construction*, such methods attempt to:

- Reduce complexity
- Eliminate wasteful activities
- Structure the supply of materials and methods of production to achieve the quickest and most reliable workflow
- Decentralize information and decision-making, to put control of processes into the hands of those most familiar with the work and most capable of improving it

Other efforts are focusing on a broader integration of the services that contribute to bringing buildings to market, including architectural and engineering design, the materials supply chain, manufacturing, prefabrication, and building construction. Such *vertical integration of construction services* into a single business entity opens up new possibilities for the streamlining of processes, application of new technologies, cost savings, elimination of waste, and control of building quality.

Advances in Information Technology

The adoption of *building information modeling* (*BIM*) and the influence of this technology on design and construction services continues to grow. Unlike the two-dimensional representation of building systems characteristic of *computer-aided design* (*CAD*), BIM is three-dimensional and intelligent. Components are not only represented geometrically and spatially but are linked to data describing their intrinsic properties and relationships to other components. In other words, the model is *object-based* and *parametric*. Originally developed for use in highly capital-intensive industries such as aerospace and automobile manufacturing, this technology is now the state-of-the-art design technology in the building construction sector.

BIM can impact all phases of the building life cycle. It can aid the design team in the effective communication of design concepts or the exploration of complex building geometries. It can improve coordination between disciplines, for example, performing *clash detection* to find spatial conflicts, or "collisions," between mechanical system ductwork, structural framing, and other systems designed by separate teams. It can facilitate the modeling of building energy use, daylighting design, and other performance criteria. For the builder, BIM can analyze project phasing, improve coordination of trades, drive the automated fabrication or preassembly of building components, and integrate cost and schedule data more closely with design and construction activities. For the building owner, information accumulated in the model during design and construction can be carried forward for use with post-occupancy operations and facilities planning. BIM has the potential to profoundly influence how buildings are designed, constructed, and operated, although the full transformative promise of this technology has yet to be realized in practice.

A key component to successful implementation of building information modeling is the *BIM execution plan*. This defines the role of the building model and its level of development at various project stages, identifies the sources of data that will contribute to the model, assigns responsibilities for authoring and managing the model, establishes protocols for information exchange among parties, and defines the technical and project infrastructure required to support these activities (Figure 1.14).

The influence of other information technologies on the design,

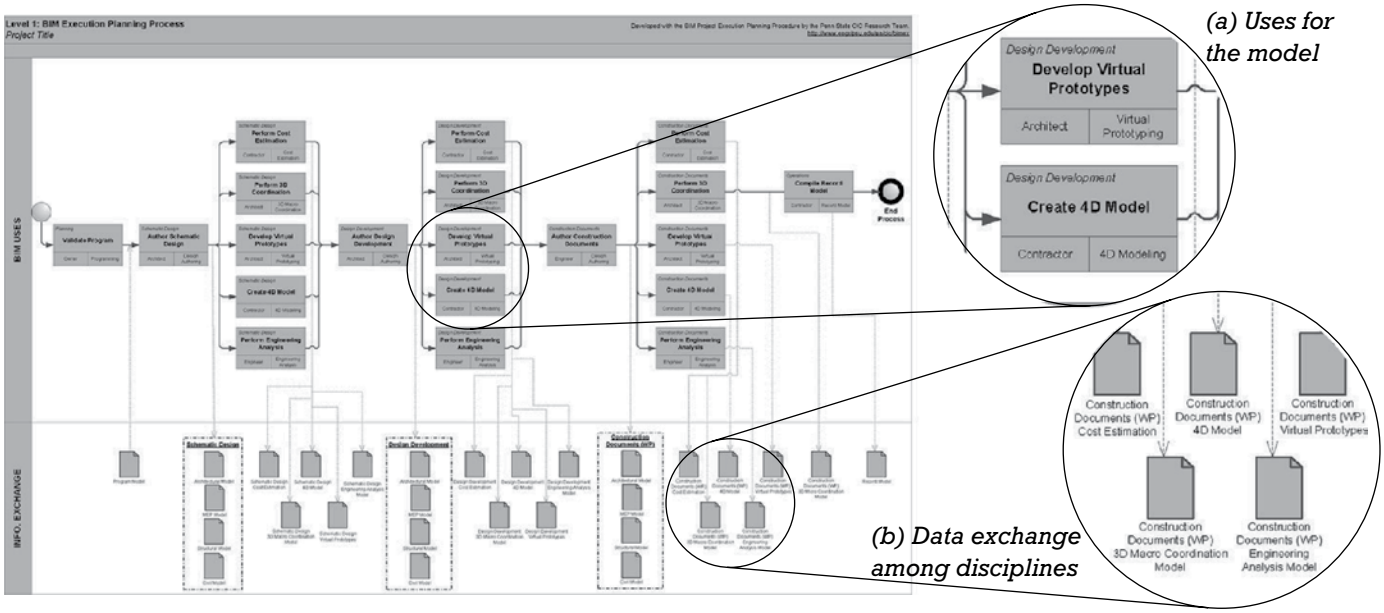


FIGURE 1.14

A sample high-level diagram of the BIM execution process through design and construction phases. Note how the model is used for numerous purposes at each phase by a variety of disciplines (*a*), while data must be exchanged regularly between disciplines in order to support the continued development of the model (*b*). *(Excerpted from the Building Information Modeling Execution Planning Guide (Version 2.1), 2011. State College, PA: Computer Integrated Construction Research Program, Pennsylvania State University. This work is licensed under the Creative Commons Attribution-Share Alike 3.0 United States License. To view a copy of this license, visit http://creativecommons.org/licenses/by-sa/3.0/us or send a letter to Creative Commons, 171 Second Street, Suite 300, San Francisco, California, 94105, USA.)*

FIGURE 1.15

At the end of each chapter, a list of MasterFormat sections relevant to the topics discussed in that chapter is included. Here, Division 0 includes sections related to the solicitation of construction services and awarding of the contract for construction. Division 1 addresses project requirements that apply broadly to all aspects of the work.

MasterFormat Sections for Procurement of Construction and General Requirements

00 10 00	**SOLICITATION**
00 11 00	Advertisements and Invitations
00 20 00	**INSTRUCTIONS FOR PROCUREMENT**
00 21 13	Instructions to Bidders
00 40 00	**PROCUREMENT FORMS AND SUPPLEMENTS**
00 41 00	Bid Forms
00 50 00	**CONTRACTING FORMS**
00 52 00	Agreement Forms
00 60 00	**PROJECT FORMS**
00 61 13	Performance and Payment Bond Form
00 70 00	**CONDITIONS OF THE CONTRACT**
01 10 00	**SUMMARY**
01 11 00	Summary of the Work
01 30 00	**ADMINISTRATIVE REQUIREMENTS**
01 31 13	Project Management and Coordination
01 32 13	Scheduling of Work
01 40 00	**QUALITY REQUIREMENTS**
01 41 00	Regulatory Requirements
01 45 00	Quality Control
01 50 00	**TEMPORARY FACILITIES AND CONTROLS**
01 70 00	**EXECUTION AND CLOSEOUT REQUIREMENTS**
01 80 00	**PERFORMANCE REQUIREMENTS**
01 81 13	Sustainable Design Requirements

construction, and operation of buildings is growing as well. Enterprise business analytics are being applied to the economics of manufacturing building components and building construction. Advanced computational methods and new data visualization techniques are opening up new possibilities for exploring the design of building systems related to structural performance, energy use, environmental impacts, and more. The networking of embedded sensors and devices within the building fabric is creating new possibilities for smart buildings that can be monitored in more detail and operated more efficiently. Big-data analysis is creating new opportunities for understanding the interactions of buildings both internally, with building occupants, and externally, with the environments within which they are placed. And robotics and 3D printing technologies are opening up new possibilities for the automated assembly and construction of building components and even complete buildings.

Key Terms

sustainable development
green building
integrated design process (IDP)
Leadership in Energy and Environmental Design, LEED
LEED prerequisite
LEED credit
Living Building Challenge
Living Building Challenge Imperative
Product Data Sheet (PDS)
environmental label, ecolabel
volatile organic compound (VOC)
product disclosure
Environmental Product Declaration (EPD)
global warming potential
Environmental Building Declaration (EBD)
ISO 14020 standards
life-cycle analysis (LCA)
cradle-to-grave analysis
environmental footprint
embodied energy
cradle-to-gate analysis
embodied water
health product declaration (HPD)
recycled materials content
preconsumer recycled material
postconsumer recycled material
bio-based material
rapidly renewable material
regional material, locally sourced material
Living Building Challenge Red List
building commissioning (Cx)
drawings
specifications
construction documents
zoning ordinance
building code
model code
National Building Code of Canada
International Building Code (IBC)
building code occupancy
building code construction type
fire resistance rating
bearing wall
nonbearing wall, partition
means of egress
International Residential Code (IRC)
Americans with Disabilities Act (ADA)
Fair Housing Act
equal access standard
Occupational Safety and Health Administration (OSHA)
ASTM International
Canadian Standards Association (CSA)
International Organization for Standardization (ISO)
American National Standards Institute (ANSI)
National Institute of Science and Technology (NIST)
Institute for Research in Construction (NRC-IRC)
trade association
Construction Specifications Institute (CSI)
Construction Specifications Canada (CSC)
MasterFormat
specification division
specification section
UniFormat
OmniClass Construction Classification System
OmniClass Tables
design/bid/build project delivery
general contractor
subcontractor
design/build project delivery
construction manager (CBA, CA)
turnkey project delivery
single-purpose entity
fixed-fee compensation, lump-sum compensation
cost plus a fee compensation
guaranteed maximum price (GMAX, GMP)
incentive provision
surety bond
performance bond
payment bond
sequential construction
phased construction, fast track construction
Gantt chart, bar chart
critical path
float
critical path method (CPM)
schedule class
schedule level
rolling schedule, look-ahead schedule
integrated project delivery (IPD)
lean construction
vertical integration of construction services
building information modeling (BIM)
computer-aided design (CAD)
object-based modeling
parametric modeling
clash detection
BIM execution plan

Review Questions

1. What is sustainable building? Why is it important?

2. What is the difference between a product disclosure and an ecolabel?

3. What is a life-cycle analysis? What are the major life-cycle stages in such an analysis?

4. What is the embodied energy of a material?

5. Who are the three principal team members involved in the creation of a new building? What are their respective roles?

6. What are construction documents? What two items are they comprised of?

7. What types of subjects are covered by zoning ordinances? By building codes?

8. What is a building code occupancy? What is a construction type? How are they related in a building code?

9. In what units is fire resistance measured? How is the fire resistance of a building assembly determined?

10. What is MasterFormat? What is it used for?

11. Compare and contrast design/bid/build and design/build construction.

12. What is the difference between lump-sum and cost plus a fee compensation?

13. What are the two common types of surety bonds? What are they used for?

14. What is fast track construction, and what types of contracts and fee compensation is it most commonly associated with?

15. What is the critical path? Why is it important to construction scheduling?

16. You are designing a three-story office building (Occupancy B) with 19,000 square feet per floor. What types of construction will you be permitted to use under the IBC if you do not install sprinklers? How does the situation change if you install sprinklers? In the second, sprinklered case, what is the least fire-resistant construction type permitted? With this construction type, what level of fire resistance is required for the structural frame of the building?

Exercises

1. Choose a building material or product. Visit the manufacturer's website and determine what types of information are available that document the material or product's sustainable attributes. Categorize the types of information available, such as product disclosures, ecolabels, EPDs, etc.

2. Choose two similar products from two different manufacturers (for example, exterior finish paints), both of which have published EPDs. Choose two life-cycle impacts, such as global warming, acidification, etc., and compare the results for the two products. Describe how the differences between the two materials might positively or negatively affect the environment or human health.

3. Apply the International Building Code to your current studio design project. What occupancies are included in your project? How large a building is permitted? What construction types may be employed? What are the minimum fire resistance ratings for the structural and nonstructural parts of the building?

4. Arrange permission to shadow an architect or CM during visits to a construction site or during project meetings related to a construction project. Take notes. Interview the architect or CM about their role and the challenges they have encountered. Report back to the class what you have learned.

Selected References

Allen, Edward, and Joseph Iano. *The Architect's Studio Companion* (6th ed.). Hoboken, NJ, John Wiley & Sons, 2017.

This design reference simplifies the determination of construction type and building size for any building according to the IBC or the National Building Code of Canada. It also gives extensive rules of thumb for structural systems, mechanical systems, egress planning, and sustainable design.

American Institute of Architects. *The Architect's Handbook of Professional Practice* (15th ed.). Hoboken, NJ, John Wiley & Sons, 2014.

Canadian Commission on Building and Fires Codes. *National Building Code of Canada.* Ottawa, National Research Council of Canada, updated regularly.

Clough, Richard H., et al. *Construction Contracting* (8th ed.). Hoboken, NJ, John Wiley & Sons, 2015.

Essentials of construction contracting and management.

Construction Specification Institute. *The Project Resource Manual, CSI Manual of Practice* (5th ed.). Alexandria, VA, 2005.

Industry-standard guidelines for organization, management, and execution of design and construction projects.

Construction Specifications Institute and Construction Specifications Canada. *MasterFormat.* Alexandria, VA, and Toronto, updated regularly.

Includes the full list of MasterFormat numbers and titles under which construction information is most commonly organized.

Deutsch, Randy. *Convergence: The Redesign of Design.* Hoboken, NJ, John Wiley & Sons, 2017.

A discussion of changes in the design and construction of buildings brought about by evolving computational tools, collaborative work processes, and digital technologies.

International Code Council. *International Building Code*. Falls Church, VA, updated regularly.

The model building code used as the basis for the majority of U.S. state, county, and municipal building codes.

International Living Future Institute. *Living Building Challenge* 3.1. Seattle, WA, updated regularly.

Describes the essential requirements for design of Living Building Certified, Petal Certified, or Net Zero Energy Certified buildings.

Kibert, Charles J. *Sustainable Construction: Green Building Design and Delivery*. Hoboken, NJ, John Wiley & Sons, 2016.

U.S. Green Building Council. *LEED v4 for Green Building Design and Construction*. Washington, DC, updated regularly.

Provides essential information for the design and construction of buildings meeting the requirements of the U.S. Green Building Council's LEED for New Construction and Major Renovations and related rating systems.

Websites

Learning to Build

Whole Building Design Guide: www.wbdg.org

Buildings and the Environment

Architecture 2030: https://architecture2030.org

Athena Sustainable Materials Institute: www.athenasmi.org

Athena Sustainable Materials Institute, Environmental Building Declarations: www.athenasmi.org/resources/publications/#environmental_building_declarations

BEES (Building for Environmental and Economic Sustainability): www.nist.gov/services-resources/software/bees

Building Green: www.buildinggreen.com

Declare: living-future.org/declare

HPD Collaborative: www.hpd-collaborative.org

International Living Building Institute: www.living-future.org

International WELL Building Institute: www.wellcertified.com

Living Building Challenge: www.livingbuildingchallenge.org

Passive House Institute US: www.phius.org/home-page

Pharos: www.pharosproject.net

U.S. Environmental Protection Agency, Green Building: www.epa.gov/greenbuilding

U.S. Green Building Council: www.usgbc.org

Worldwatch Institute: www.worldwatch.org

The Work of the Design Professional

American Institute of Architects: www.aia.org

American National Standards Institute (ANSI): www.ansi.org

ASTM International: www.astm.org

Canadian Standards Association (CSA): www.csa.ca

Construction Specifications Canada (CSC): www.csagroup.org

Construction Specifications Institute (CSI): www.csiresources.org

International Code Council: www.iccsafe.org

International Codes, Public Access: https://codes.iccsafe.org/public/collections/I-Codes

National Institute of Building Sciences (NIBS): www.nibs.org

NRC Institute for Research in Construction: www.nrc-cnrc.gc.ca/eng/rd/construction

OmniClass: www.omniclass.org

UniFormat: www.csiresources.org/practice/standards/uniformat

The Work of the Construction Professional

AACE International: web.aacei.org

Associated General Contractors of America (AGC): www.agc.org

Building Owners and Managers Association (BOMA): www.boma.org

Construction Management Association of America (CMAA): cmaanet.org

Design-Build Institute of America (DBIA): www.dbia.org

Engineers Joint Contract Documents Committee: www.ejcdc.org

Trends in the Delivery of Design and Construction Services

ConsensusDocs: www.consensusdocs.org

Construction Robotics: www.construction-robotics.com

Core Studio, Thornton Tomasetti: core.thorntontomasetti.com/core-studio

ICON: www.iconbuild.com

Integrated Project Delivery: A Guide: www.aiacontracts.org/resources/64146-integrated-project-delivery-a-guide

Katerra: katerra.com

Lean Construction Institute: www.leanconstruction.org

U.S. National BIM Standard: www.nationalbimstandard.org

FRANKI
HALLEMORE

2

Foundations and Sitework

- **Foundation Requirements**
- **Earth Materials**
  - Classifying Earth Materials
  - Properties of Soils
  - Soils for Building Foundations
  - Subsurface Exploration and Soils Testing

Sustainability and Foundations and Sitework

- **Earthwork and Excavation**
  - Excavation
  - Excavation Support
  - Contiguous Piers
  - Dewatering
- **Foundations**
  - Shallow Foundations
  - Deep Foundations
  - Seismic Base Isolation
  - Underpinning
  - Up–Down Construction
- **Foundations as Building Enclosure**
  - Waterproofing and Drainage
  - Thermal Insulation
  - Radon and Soil Gas Control
- **Sitework**
  - Retaining Walls
  - Earth Reinforcing
  - Filling and Finish Grading
- **Designing Foundations**
- **Foundations and the Building Code**

Foundation work in progress for a midrise hotel and apartment building. The earth surrounding the excavation is retained with steel sheet piling supported by steel walers and tiebacks. Equipment enters and leaves the site via the earth ramp at the bottom of the picture. Although a large backhoe at the right continues to dig around old piles from a previous building on the site, the installation of pressure-injected concrete pile footings is also well underway, with several piledrivers at work in the near and far corners and clusters of completed piles visible in the center of the picture. Concrete pile caps and column reinforcing are under construction in the center of the excavation. *(Courtesy of Franki Foundation Company.)*

The function of a *foundation* is to transfer structural loads reliably from a building into the ground. Every building must have a foundation of some kind: A backyard toolshed will not be damaged by slight shifting of its foundation and thus may need only wooden skids to spread its load across an area of the ground surface sufficient to support its weight. A wood-framed house needs greater stability than a toolshed, so its foundation reaches through the unstable surface to underlying soil that is free of organic matter and unreachable by winter frost. A larger building of masonry, steel, or concrete weighs many times more than a house, and its foundations must penetrate the earth until they reach soil or rock that is capable of carrying its massive loads; on some sites, this means going 100 feet (30 m) or more below the surface. Foundation design is a specialized field that must account for the interaction of building loads with the various soil, rock, and water conditions encountered below the surface of the ground. The choice of foundation type can have a significant impact on building costs, construction schedule, and choice of structural systems for the remainder of the building.

Foundation Requirements

The most important role of the foundation is to prevent building collapse. The foundation must receive the various loads acting on the building and transfer these loads into the underlying earth in a manner such that the building remains upright and stable (Figure 2.1). These loads may include:

- *Dead load*, the combined weight of all the permanent components of the building, including its own structural frame, floors, roofs, and walls, major permanent electrical and mechanical equipment, and the foundation itself
- *Live loads*, nonpermanent loads caused by the weights of the building's occupants, furnishings, and movable equipment
- *Rain* and *snow loads*, which act primarily downward on building roofs
- *Wind loads*, which can act laterally (sideways), downward, or upward on a building
- *Seismic loads*, dynamic horizontal and vertical forces caused by the motion of the ground relative to the building during an earthquake
- Loads caused by soil and hydrostatic pressure, including *lateral soil pressure loads* consisting of horizontal pressures of earth and groundwater against basement walls; in some instances, *buoyant uplift* forces from underground water, identical to the forces that cause a boat to float; in other instances, lateral force *flood loads* that can occur in areas prone to flooding
- In some buildings, *horizontal thrusts* from long-span structural components, such as arches, rigid frames, domes, vaults, or tensile structures

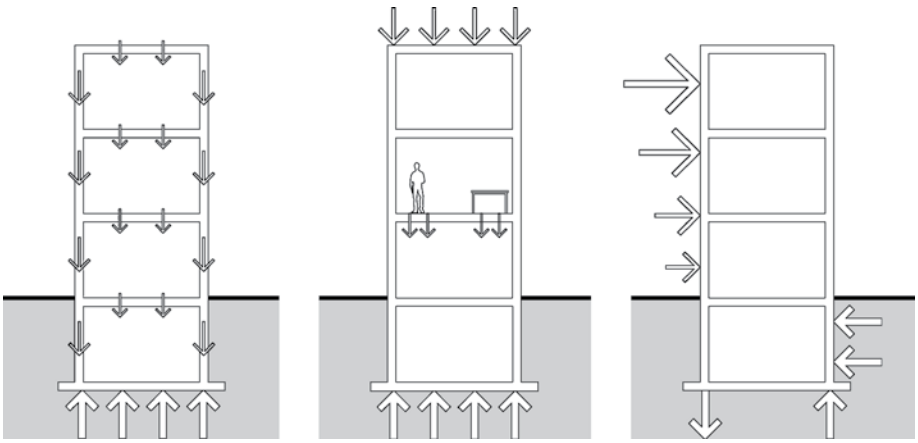


Figure 2.1
Some of the loads that act on buildings. Under any combination of possible load scenarios, the foundation must reliably transmit the forces acting upon the building into the ground in a manner such that the building remains stable.

Foundations must limit *settlement*. All foundations settle to some extent as the surrounding earth compresses and adjusts to the loads imposed by the building above. Over the life of the building, settlement must not exceed amounts that would cause structural distress, damage nonstructural components, or interfere with building functions.

Foundations on bedrock settle a negligible amount. Foundations in other types of soil may settle more but are normally designed to limit settling to amounts measured in millimeters or fractions of an inch. In rare cases, buildings may settle by significantly greater amounts. Mexico City's Palace of Fine Arts, for example, has sunk roughly 13 feet (4.0 m) into the clay soil on which it is founded since it was constructed in the early 1930s.

We must never trust too hastily to any ground. . . . I have seen a tower at Mestre, a place belonging to the Venetians, which, in a few years after it was built, made its way through the ground it stood upon . . . and buried itself in earth up to the very battlements.

—Leon Battista Alberti, *Ten Books on Architecture*, 1452

Where settling occurs at roughly the same rate throughout all parts of a building, it is termed *uniform settlement*. When parts of a building settle differently, it is called *differential settlement*. Differential settlement can lead to distortion of the building frame, sloped floors, cracked walls and glass, or inoperable doors and windows (Figure 2.2). Most foundation failures are attributable to excess differential settlement. Gross failure of a foundation, in which the soil fails completely to support the building, is rare.

Where foundations enclose basements or other usable space, they must keep those spaces dry and at a comfortable temperature. Where foundations are constructed close to other existing buildings, they must not impose new loads or alter ground conditions in ways that could adversely affect those nearby buildings. Furthermore, foundations must be feasible to construct, both technically and economically. These and other aspects of foundation design are discussed at more length in this chapter.

Earth Materials

Classifying Earth Materials

For the purposes of foundation design, *earth materials* are classified according to particle size, the presence of organic content, and, in the case of finer-grained soils, sensitivity to moisture content.

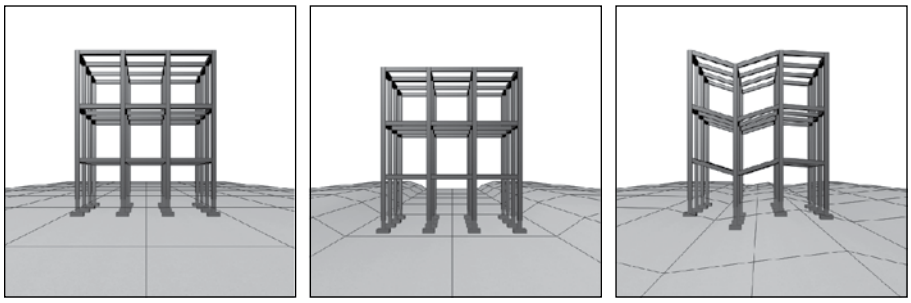
Consolidated rock, or *bedrock*, is a dense, continuous mass of mineral materials that can be removed only by drilling, fracturing, or blasting. Rock is rarely completely monolithic and may vary in composition or structure, or be crossed by systems of joints (cracks). Despite such variations, bedrock is generally the strongest and most stable material on which a building can be founded.

Soil is a general term referring to any earth material that is particulate. Particulate soils are further defined according to ASTM D2487, Unified Soil Classification System (Figure 2.3), as follows:

- *Boulders* are greater than 12 inches (300 mm) in diameter.
- *Cobbles* are smaller than boulders but greater than 3 inches (75 mm) in diameter.
- *Gravel* is from 3 inches to 0.187 inches (75 mm to 4.75 mm) in diameter.
- *Sand* is from 0.187 inches to 0.003 inches (4.75 mm to 0.07 mm) in diameter.
- Gravel and sand are also collectively referred to as *coarse-grained soils*.
- *Silt* particles are smaller than 0.0029 inches (0.075 mm). Like sand and gravel, silt particles are roughly spherical in shape.
- *Clay* particles are also defined as smaller than 0.0029 inches (0.075 mm), though typically they are an order of magnitude (10 times) or more smaller. Also, unlike larger-grained particles, they are flat or plate-shaped rather than spherical.
- Both silts and clays are also referred to as *fine-grained soils*.

In the field, major soil types can be roughly distinguished with simple hand tests. It takes two hands to lift a boulder and one to lift a cobble. If you can easily lift just one particle between two fingers, it is gravel. If individual soil particles are large enough to be seen, but too small to be picked up singly, they are sand. If particles are too small to see with the unaided eye, they are silt or clay. When wet, clay soils are putty-like; when dry, they are hard. Silts are not sticky when wet and have little or no cohesiveness when dry.

Peat, topsoil, and other *organic soils* are not suitable for the support of building foundations. Their organic matter content makes them spongy and sensitive to changes in water content or biological activity within the soil.



(*a*) *Building before settlement occurs* (*b*) *Uniform settlement* (*c*) *Differential settlement*

Figure 2.2
Uniform settlement (*b*) is usually easily controlled and of little consequence in a building. Differential settlement (*c*) is more likely to lead to damage to finishes or the building structure.

Properties of Soils

Particle Size

Coarse-grained soils—sands and gravels—consist of relatively large mineral particles with little or no

				Group Symbol	Descriptive names of soil within this group
Coarse-Grained Soils	Gravels	Clean Gravels		GW	Well-graded gravel or well-graded gravel with sand, little or no fines
				GP	Poorly graded gravel or poorly graded gravel with sand, little or no fines
		Gravels with Fines		GM	Silty gravel, silty gravel with sand
				GC	Clayey gravel, clayey gravel with sand
	Sands	Clean Sands		SW	Well-graded sand or well-graded sand with gravel, little or no fines
				SP	Poorly graded sand or poorly graded sand with gravel, little or no fines
		Sands with Fines		SM	Silty sand, silty sand with gravel
				SC	Clayey sand, clayey sand with gravel
Fine-Grained Soils	Silts and Clays	Liquid Limit < 50		ML	Silt or silt-sand-gravel mixtures, low plasticity
				CL	Lean clay or clay-sand-gravel mixtures, low plasticity
				OL	Organic clay or silt (clay or silt with significant organic content), or organic clay- or silt-sand-gravel mixtures, low plasticity
		Liquid Limit ≥ 50		MH	Elastic silt, silt-sand-gravel mixtures
				CH	Fat clay or clay-sand-gravel mixtures, high plasticity
				OH	Organic clay or silt (clay or silt with significant organic content), or organic clay- or silt-sand-gravel mixtures, high plasticity
Highly Organic Soils				PT	Peat, muck, and other highly organic soils

FIGURE 2.3
The Unified Soil Classification System, from ASTM D2487. The two-letter Group Symbols are a universal set of abbreviations for soil types, as seen, for example, in Figure 2.6.

attractive or repulsive forces acting between them. The ability of these soils to support building loads without shifting depends primarily on friction between the particles to keep the particles from sliding past one another. This resistance to internal sliding, called *shear strength*, varies with the degree of interlocking between particles and the confining force of the surrounding soil. Where coarse-grained soils are densely packed and securely confined by surrounding soils, it is relatively difficult for particles to move past one another. Soils such as these exhibit relatively high strength. Where coarse-grained soils are loosely packed or poorly confined, particles can more easily slide past one another, and less load can be safely supported. Soils that rely primarily on internal friction for strength are termed *frictional* or *cohesionless*.

Smaller-grained soils may be subject to a wider array of interparticle forces. As particle size decreases, surface area increases in relation to weight and size, and the spaces between the particles, called *soil pores*, get smaller. In essence, the particles become lighter and more easily pushed and pulled by electrostatic forces, chemical interactions, and forces related to the presence of water in the soil.

For example, whereas gravels are generally little affected by moisture in the soil, the properties of sand can vary noticeably with moisture content. As any beachgoer knows, wet sand makes a stronger sand castle than dry sand, as capillary forces acting between particles help to hold the particles in place. And wet sand responds more firmly to the pressure of our feet as we walk on the beach than does dry sand, as the hydrostatic pressure of the water helps to distribute the load exerted on the soil. A dramatic example of the effects of moisture on smaller-grained soils is a phenomenon called *soil liquefaction*. Water-saturated sands or silts may lose virtually all of their strength and behave as a liquid when subjected to sudden, large changes in load, such as may occur during an earthquake.

Clay particles are extremely small in size and flatter in shape, making the ratio of their surface area to volume hundreds or thousands of times greater than even silts. They also differ in mineral composition from larger-grained soils and tend to arrange themselves into more complex internal structures, called *fabric*, as particles aggregate into sheetlike or other geometric arrangements.

As a result, clay soils tend to stick together and are characterized as *cohesive* rather than frictional. For example, it may be possible to dig a vertical-walled excavation in clay soil without temporary soil support (Figure 2.4). There is sufficient shear strength in the unconfined soil to prevent the excavation walls from collapsing. In contrast, a cohesionless soil such as sand must be excavated at a shallower angle to avoid the collapse of unsupported walls. Cohesive soils tend to be hard when dry and moldable, or *plastic*, when moist. They also have what is called a higher *liquid limit* than more coarsely grained soils. That is, they can sustain a higher moisture content before arriving at a flowable consistency. Silts may also exhibit cohesive properties, but to a lesser extent than clays.

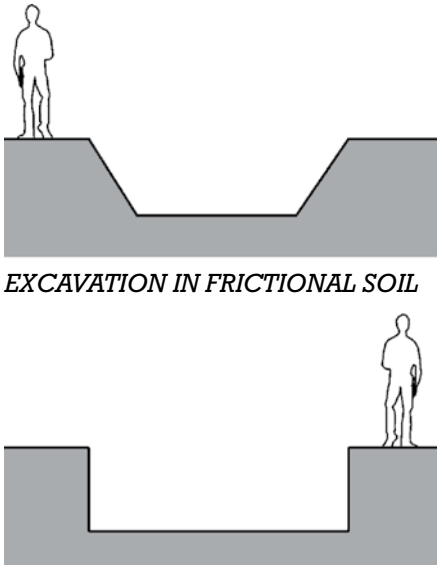


Figure 2.4
Excavations in frictional and highly cohesive soils.

Clay soils may also be *expansive*, that is, prone to expand or contract with changes in moisture content. Clays with very small particle size and high liquid limits are most susceptible to this behavior. Highly expansive soils can increase in volume by 10 percent or more with increased moisture content, and with sufficient force to cause damage to the building structure if not properly accounted for in the design of the foundation.

The unique properties of clay soils tend to cause water to pass through them very slowly, or in some cases not at all. In fact, some clay soils are incorporated into sheet materials and used as waterproofing for basements and other underground structures.

Gradation

Within any soil sample, the range of particle sizes present, or *gradation*, may vary. A *well graded* soil includes a broad, well-distributed range of particle sizes. A *poorly graded* soil consists of particles more limited in range of sizes. Well graded soils contain less empty space between particles than poorly graded soils, as smaller particles fill in gaps between larger ones. Broadly speaking, well graded soils tend compact more effectively than poorly graded ones, but also tend to drain water less readily.

When deliberately prepared for use in earthwork, soil materials may be purposefully graded in specific ways: A *uniformly graded* material is composed of particles within a limited, narrow size range (Figure 2.5). This produces the maximum possible

Figure 2.5
Two gravel samples, illustrating differences in gradation. The left-hand sample, with a broad range of particle sizes, comes from a well graded sandy gravel. On the right is a uniformly graded gravel sample in which there is little variation in size among particles.
(Photos by Joseph Iano.)

volume of empty space within the material. A *gap graded* soil contains a broader range of particle sizes, but with certain sizes omitted. For example, aggregates for pervious concrete, as described in Chapter 13, may be gap graded. This ensures a sufficient particle size distribution to produce a strong concrete that also includes sufficient void space such that stormwater can effectively drain through the finished pavement.

The term "sorting" can also be used to describe particle size distribution within a soil, but with the opposite sense of grading. That is, a well graded soil is *poorly sorted* and poorly graded soil is *well sorted.*

Soils for Building Foundations

Generally, soil groups listed toward the top of Figure 2.3 are better suited for supporting building foundations than those listed further down. Those closer to the top of the list exhibit greater loadbearing capacity and stability and are less sensitive to moisture content. Consolidated rock is usually the strongest material on which to set a building. Usually, however, such rock is too deep to be reached economically, and the foundation is designed to bear on some other particulate stratum closer to the ground surface. An often-cited example of the suitability of continuous rock for large building foundations is the historic clustering of tall buildings in New York City toward the central portion of Manhattan Island. This is the portion of the island where the bedrock is closest to the surface and the massive foundations needed for these buildings can be constructed most easily and inexpensively.

Figure 2.6 gives values for *allowable foundation pressures* (or *allowable soil pressures*) for common classes of soil materials. These figures may be used for the design of small building foundations where analysis of soil samples from the site is deemed unnecessary. The allowable pressures are significantly less than the maximum capacities of the soils, accounting for uncertainties in soil composition and properties, design factors of safety, and acceptable settlement limits. For larger buildings, or on sites with questionable soil conditions, soil properties are determined through site investigation and laboratory tests.

Rock and coarse-grained soils are also generally the most stable materials for supporting foundations, behaving more consistently under varying moisture content than fine-grained soils. Clay soils, in particular, can present unique challenges. When clay with high moisture content is put under continuous pressure, water can be slowly pressed out of it, with a corresponding gradual reduction in soil volume, a behavior called *consolidation.* Where such a soil stratum underlies a foundation, the possibility of long-term settlement must be considered. Or, as noted earlier, where highly expansive clays are present, provisions may be required to allow the clay to expand without causing damage to the building substructure. In regions of significant earthquake risk, soil stability during seismic events must be considered, such as sliding of steep slopes or soil liquefaction.

In addition to foundation support, *imported soil* materials (those

TABLE 1804.2
ALLOWABLE FOUNDATION AND LATERAL PRESSURE

CLASS OF MATERIALS	ALLOWABLE FOUNDATION PRESSURE (psf)[d]	LATERAL BEARING (psf/f below natural grade)[d]	LATERAL SLIDING	
			Coefficient of friction[a]	Resistance (psf)[b]
1. Crystalline bedrock	12,000	1,200	0.70	—
2. Sedimentary and foliated rock	4,000	400	0.35	—
3. Sandy gravel and/or gravel (GW and GP)	3,000	200	0.35	—
4. Sand, silty sand, clayey sand, silty gravel and clayey gravel (SW, SP, SM, SC, GM and GC)	2,000	150	0.25	—
5. Clay, sandy clay, silty clay, clayey silt, silt and sandy silt (CL, ML, MH and CH)	1,500[c]	100	—	130

For SI: 1 pound per square foot = 0.0479kPa, 1 pound per square foot per foot = 0.157kPa/m.
a. Coefficient to be multiplied by the dead load.
b. Lateral sliding resistance value to be multiplied by the contact area, as limited by Section 1804.3.
c. Where the building official determines that in-place soils with an allowable bearing capacity of less than 1,500 psf are likely to be present at the site,the allowable bearing capacity shall be determined by a soils investigation.
d. An increase of one-third is permitted when using the alternate load combinations in Section 1605.3.2 that include wind or earthquake loads.

FIGURE 2.6

Allowable bearing values for various soil types, from the IBC. The soil class abbreviations in rows 3, 4, and 5 make reference to the group symbols in Figure 2.3. *(Excerpted from the 2012 International Building Code, Copyright 2011. Washington, DC: International Code Council. Reproduced with permission. All rights reserved. www.ICCSAFE.org)*

brought from offsite) may be used for backfilling excavations, construction of base layers under pavements and concrete slabs at grade, finish grading for landscaping, or replacement of unsuitable *native soils* (those already present at the building site). In each case, materials with appropriate strength and stability, drainage capacity, compaction characteristics, and organic content are selected.

For example, for *general-purpose fill*, good compaction and stability are important. Here, a well graded, coarse-grained soil is likely a good choice. However, directly around the foundation, a more porous *drainage fill*, that can efficiently transport water toward foundation drains, may be required, and a graded material with fewer fines may be preferable (see Figure 2.54).

FIGURE 2.7
A truck-mounted drilling rig performing test borings at a site planned for future construction. Equipment of this type is capable of boring into the ground 1000 feet (300 m) or more. The drilling auger can be seen just off the back of the truck bed. Hydraulic jacks, just slightly forward and to either side of the auger, level and stabilize the drilling platform. A pair of drill operators is preparing to connect a new length of drilling pipe while, to the left, a technician oversees the drilling and collects soil samples. *(Photo by Joseph Iano.)*

Subsurface Exploration and Soils Testing

For all but small buildings, foundation design is preceded by investigation of soil conditions at the site. *Test pits* can be dug when the foundation will not extend deeper than roughly 16 feet (3 m), the maximum practical reach of small excavating machines. Soil strata and subsurface water conditions can be observed in the pit and samples taken for evaluation.

Water below the ground surface is called *groundwater,* and the elevation at which soil is fully saturated with groundwater is called the *water table.* If the water table lies within the depth of a test pit dug in coarse-grained soils, it will be readily apparent, as the pit will quickly fill with water up to that level. Test pits excavated in less permeable fine-grained soils may not easily reveal the water table level, as groundwater may seep only slowly through the soil. In such cases, the water table level can be determined with a separately drilled observation well or devices that measure water pressure within the soil.

Where open test pits are not practical or information at greater depths is required, *test borings* are performed with portable drilling rigs (Figure 2.7). As boring progresses, soil conditions are evaluated at regular intervals and especially as differing soil strata are encountered. Soil density and potential bearing capacity are evaluated by counting hammer blows on an open-ended hollow tube called a *penetration sampler* as it is advanced a standard distance into the borehole. Samples extracted from the boring are examined in the field and frequently also taken for laboratory testing. Test borings can return information on each soil stratum, such as soil type, depth, and thickness, as well as groundwater conditions (Figure 2.8). Usually, a number of borings are taken around a site. The information from each is mapped and the results interpolated to create a fuller picture of subsurface conditions for use by the foundation engineer.

Load tests also may be performed on the construction site to further evaluate the bearing capacity and stability of the soil. Where bearing soils are exposed by test pits, a temporary framework supporting large concrete blocks may be constructed to apply a static (constant) load to the exposed soils and observe their response over a period of days or weeks. Where deeper foundations—for example, friction piles, as discussed later in this chapter—are used, static or dynamic (controlled impact) loading of these elements may be used to verify that the intended bearing strata have been reached and that the strata and foundation elements are behaving as predicted.

In the laboratory, soil samples are dried and then particle gradation is determined using a collection of *sieves* with wire mesh screens of varying spacing. As a soil sample is passed through consecutively finer sieves, particles of differing size ranges are separated and the relative

EXPLORATORY BORING LOG EB-6

SURFACE ELEVATION: 118 FT

DESCRIPTION	CONSISTENCY	CLASSIFICATION	DEPTH (FT)
Dark brown, Sandy Lean Clay, moist, moderate plasticity, fine to medium sand, reddish-brown mottling, the upper portion appears to be fill or reworked native soil.	Hard	CL	0
Gray, Sandy Lean Clay, moist, moderate plasticity, fine to coarse sand, tan and light orange mottling. LL=38, PL=20	Very Stiff	CL	
Gray to brown, Clayey Sand, moist, fine to coarse sand, fine rounded to angular gravel, light orange mottling, moderately plastic fines. 40% passing No. 200 Sieve. ▼ Ground water measured at 6 ft after drilling. ▼ Ground water encountered during drilling at 8.5 ft.	Medium Dense to Dense	SC	5 10
Gray, Sandy Lean Clay, moist, moderate plasticity, fine sand.	Stiff	CL	15
Brown, Poorly Graded Sand, moist, fine to coarse sand. Bottom of boring at 20.5 ft.	Dense	SP	20

FIGURE 2.8

An example of a log from a test boring indicating the type of soil in each stratum and the depth at which it was encountered. Depths at which groundwater were found are also recorded. The Classification abbreviations correspond to the Unified Soil Classification System as explained in Figure 2.3.

proportions of each quantified. For very fine soils, particle size is determined by mixing the soil with water and observing how rapidly particles precipitate out of liquid suspension (larger particles will fall to the bottom of the mixture more rapidly than smaller ones).

For cohesive soils, properties such as the liquid limit and *plastic limit* (the water content at which the soil transitions from solid to plastic) are determined. Additional tests can determine soil water content, permeability, liquefaction potential, chemical constituents, expansion potential, strength in shear and compression, and consolidation potential (Figure 2.9).

The information gained through subsurface exploration and laboratory testing is summarized in a written *geotechnical report*. This report may include recommendations for allowable bearing loads for the various soil strata, appropriate foundation types, estimated rates of foundation settlement, soil drainage and foundation waterproofing, and other relevant information. This report is used by engineers in the design of excavations, excavation support systems, dewatering, building foundations, and substructure. It is also used by contractors in the planning and execution of their sitework during construction.

FIGURE 2.9

In a triaxial load test, a soil sample is loaded axially by the piston and circumferentially by water pressure in the transparent cylinder. *(Courtesy of Ardaman and Associates, Inc., Orlando, Florida.)*

Sustainability and Foundations and Sitework

Building sites should be selected and developed to protect and conserve natural habitats and resources, enhance sustainable community development patterns, promote biodiversity, preserve quality open space, and minimize pollution and unnecessary energy consumption.

Site Selection and Land Protection

- Building within densely populated areas with existing infrastructure and amenities—rather than in areas unconnected to community resources—promotes neighborhood vitality, reduces private motor vehicle travel, and protects undeveloped open space.
- Building on a previously developed, damaged, or polluted *brownfield* site, and designing the building so that it restores that site, helps to mitigate previous environmental degradation.
- Selecting a building site that is well connected to existing networks of public transportation, bicycle routes, and pedestrian paths reduces fuel consumption, air pollution, and other adverse impacts of private motor vehicle use.
- Avoiding construction on prime agricultural land preserves productive land for the future.
- Avoiding construction on undeveloped, environmentally sensitive land protects the wildlife and natural habitats that such land supports. This includes floodplains, land that provides habitat for endangered or threatened species, wetlands, mature forest lands and prairies, and land adjacent to natural bodies of water.
- Avoiding construction on public parkland or land adjacent to recreational bodies of water preserves public open space and recreational resources.

Site Design

- Preservation of mature trees, distinctive topographic formations, recreational pathways, and other unique site features prevents the loss of irreplaceable site assets.
- Minimizing the building footprint preserves open space.
- Protecting and enhancing unbuilt portions of the site with native vegetation preserves green space and animal habitat and helps maintain biodiversity.
- Appropriate landscape design and plant selection minimizes the need for landscape irrigation and unneeded water consumption.
- Minimizing impervious ground surface area and providing drainage systems that allow the reabsorption of stormwater into the ground work to maintain the natural hydrology of the building site, reduce demand on municipal storm sewer systems, and protect natural waterways from overloading and pollution.
- Providing shaded or reflective paving reduces heat island effects and creates an improved microclimate for both humans and wildlife.
- Minimizing nighttime light pollution is a benefit to humans and nocturnal wildlife alike.
- Siting a building for optimal exposure to sun and wind maximizes opportunities for passive heating and cooling, and natural daylighting, all of which are strategies that reduce building energy consumption and enhance occupant well-being and productivity.
- Avoiding unnecessary shading of adjacent buildings protects those buildings' sources of natural illumination and useful solar heat.

Site Work

- Maintaining landscape protection during construction prevents the loss of difficult- or impossible-to-replace trees and vegetation.
- Erosion-control measures during construction minimize the loss of soil by wind or water action, prevent sedimentation of streams and sewers, and minimize pollution of the air with dust or particulates.
- Well-marked and properly prepared construction vehicle access ways prevent overcompaction of soils and minimize noise, dust, air pollution, and inconvenience to neighboring buildings and sites.
- Recycling of construction wastes diverts solid waste from permanent landfills.

Energy Performance

- Properly insulated basements reduce building energy consumption and improve occupant comfort.

Building and Material Life-Cycle Impacts

- Restoring or renovating an existing building, rather than constructing a new one, saves energy and building materials. By avoiding demolition, renovation also diverts enormous quantities of waste material from landfill.

Unhealthful Materials and Emissions

- In areas of high radon or other soil gas risk, barrier and venting systems protect building occupants from exposure to unhealthful emissions or gasses.

Earthwork and Excavation

Virtually all building construction is accompanied by at least some form of *earthwork* during construction. On undeveloped sites, construction may begin with *grubbing and clearing*, in which trees and plants, stumps, large roots, and other surface materials are removed with heavy machinery. Next, organically rich topsoil may be scraped away and stockpiled to one side to await reuse at the end of construction.

Excavation

Excavation is necessary for basement construction, to reach undisturbed, adequately firm soil for shallow footings; for trenches for buried utilities; and to remove native soils that are contaminated or too weak or unstable to build over.

In particulate soils, any of a wide variety of machines, such as bulldozers, backhoes, bucket loaders, scrapers, trenching machines, and others, may be used to loosen and lift the soil from the ground. If the soil must be moved more than a short distance, dump trucks come into use.

In rock, excavation is slower and many times more costly. Weak or highly fractured rock may be broken up with power shovels, pneumatic hammers, or other specialized equipment. Blasting, in which explosives are placed and detonated in lines of closely spaced holes drilled into the rock, may also be used. Where blasting is impractical, hydraulic splitters, devices inserted into similarly drilled holes but that rely on driven wedges to split the rock, may be used.

Excavation Support

If the construction site is sufficiently larger than the area to be covered by the building, the edges of the excavation can be sloped back or *benched* at a low enough angle that the soil will not slide back into the hole. This angle, called the *maximum allowable slope* or *angle of repose*, can be steep for cohesive soils such as stiff clays or shallower for frictional soils such as sand and gravel. On constricted sites, the soil surrounding an excavation must be held back by some kind of *excavation support* capable of resisting the pressures of earth and groundwater (Figure 2.10). Excavation support can take many forms, depending on the soil type, depth of excavation, type of construction to follow, equipment and preferences of the contractor, proximity of surrounding roads or buildings, and presence of groundwater.

Shoring

Shoring is construction used to support the sides of an excavation and prevent its collapse. For large excavations, the most common types of shoring are soldier beams and lagging, and sheet piling. With soldier beams and lagging, steel columns called *H-piles*, or *soldier beams*, are driven vertically into the earth at close intervals around an excavation site before digging begins. As earth is removed, the *lagging*, frequently consisting of heavy wood planks, is placed against the flanges of the columns to retain the soil outside the excavation (Figures 2.11 and 2.12). *Sheet piling* or *sheeting* consists of vertical sheets of various materials that are aligned

Figure 2.10
On a spacious site, excavation can be benched. When excavating close to property lines or nearby buildings, some form of excavation support, such as sheeting, is used to retain the soil around the excavation.

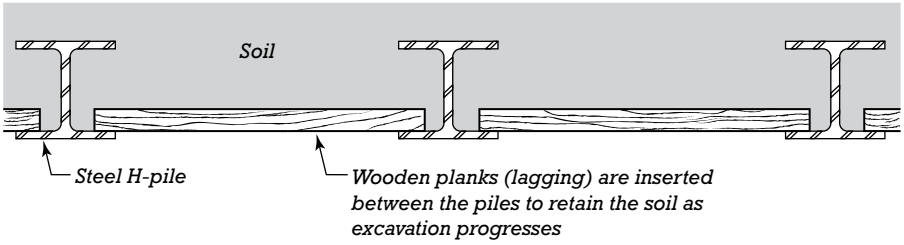


Figure 2.11
Soldier beams and lagging, shown in horizontal (plan) section.

FIGURE 2.12
Soldier beams and lagging. Lagging planks are added at the bottom as excavation proceeds. The drill rig is boring a hole for a tieback (explained later in this chapter) to brace a soldier beam. *(Courtesy of Franki Foundation Company.)*

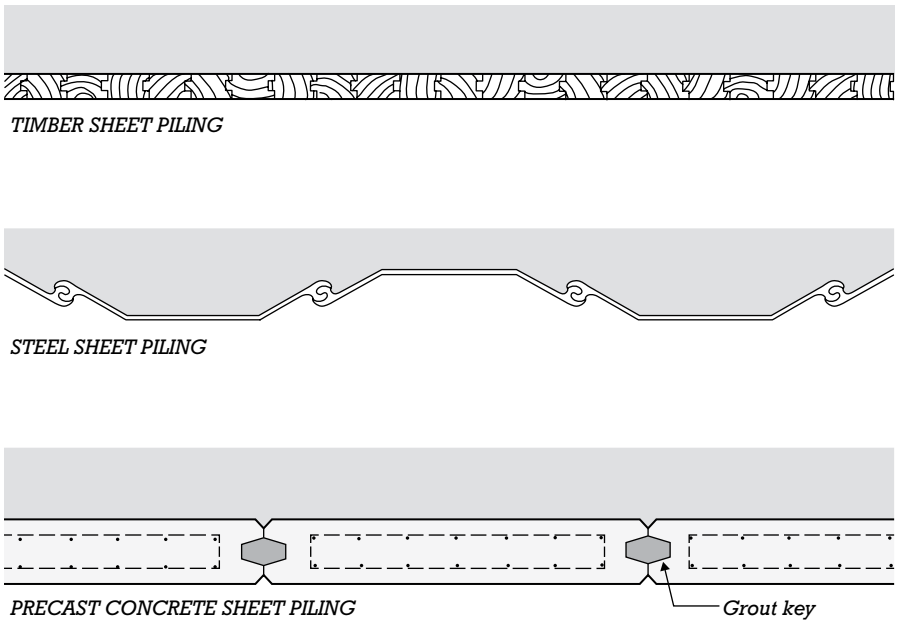


FIGURE 2.13
Horizontal (plan) sections through three types of sheet piling. The shading represents the retained earth.

tightly against one another edge-to-edge and driven into the earth to form a solid wall, also before excavation begins (Figures 2.13 and 2.14). The most common material for sheet piling is steel, but wood, aluminum, PVC plastic, composite polymers, or precast concrete may also be used. For trench work, a variety of easy-to-deploy, reusable support systems are also used.

Most often, shoring is temporary and is removed as soil is replaced in the excavation. However, it may also be left in place to become a permanent part of the building's substructure. This may be necessary, for example, where shoring is located close to a property line and there is no practical way to remove it after completion of construction without disturbing the adjacent property.

Where soil is sufficiently cohesive to hold an adequate slope at least temporarily, excavations can be stabilized with *pneumatically applied concrete*, also called *shotcrete*. This stiff concrete mixture is sprayed directly from a hose onto the soil shortly after the soil is excavated. The hardened concrete reinforces the slope and protects against erosion (Figure 2.15).

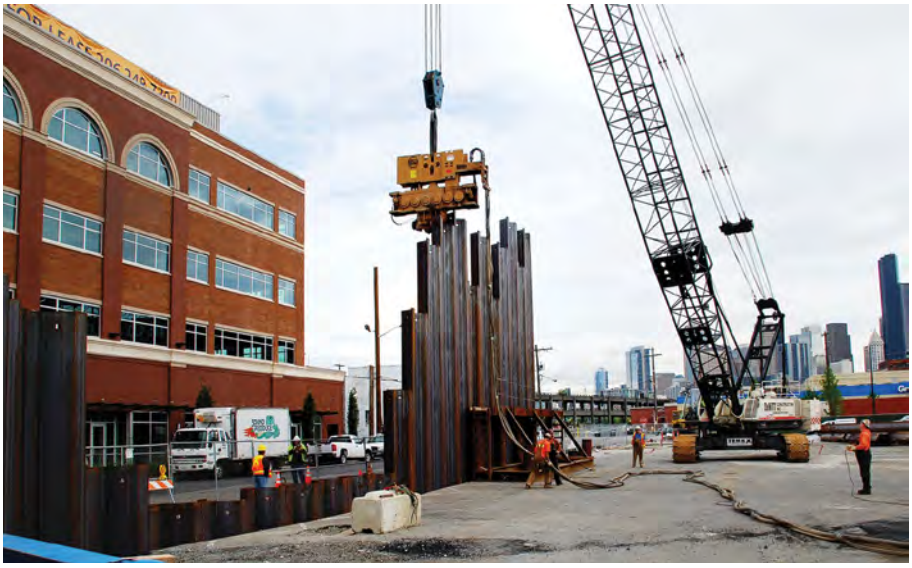


FIGURE 2.14
Steel sheet piling being installed with a vibratory driver. The driver imparts a rapid up-and-down motion to the sheets. This causes temporary liquefaction of the soil directly under the leading edge of the sheet, allowing the sheet to descend easily into the soil. Depending on soil conditions, impact hammers or hydraulic presses may also be used. The circular hole in the top of each of sheet is used when lifting the sheets by crane. *(Photo by Joseph Iano.)*

FIGURE 2.15
Where excavation support turns the corner and the soil can be sloped less steeply, soldier beams and lagging come to an end and shotcrete is used to stabilize the soil. *(Photo by Joseph Iano.)*

Soil Mixing

With *soil mixing*, the sides of an excavation are strengthened by blending portland cement and water with the existing soil. Mixing occurs in place, using rotating augers or paddles lowered into the ground. The soil-cement mix hardens into a series of underground, abutting vertical cylinders of low-strength concrete against which excavation can proceed (Figure 2.16). Where bracing is required (as discussed later in this chapter), soldier piles can be inserted into the soil-cement mix before the mix hardens, to become part of the bracing structure (Figure 2.17). Soil-mixed excavation support always remains in place, becoming a permanent part of the subgrade construction.

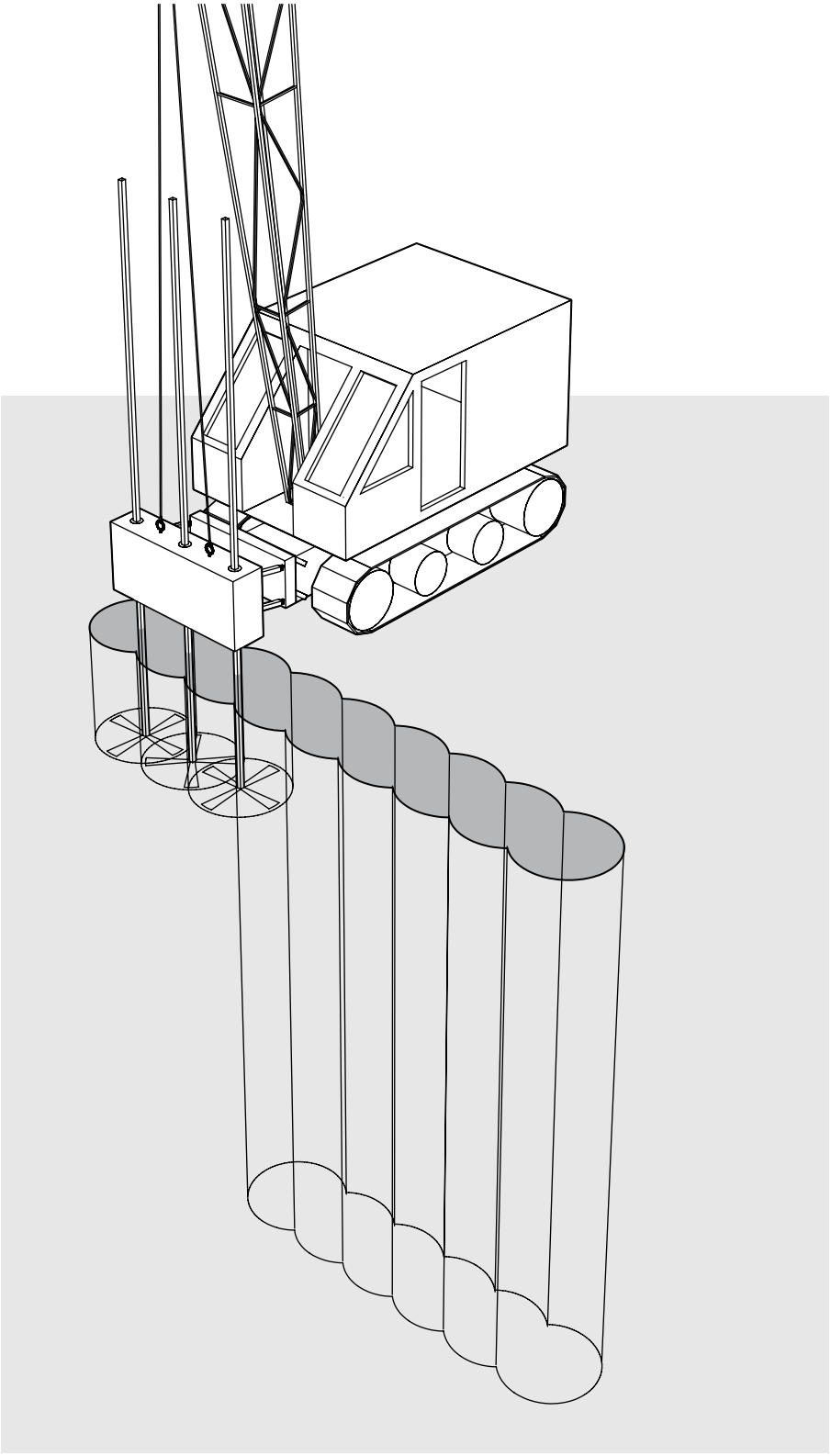


FIGURE 2.16
Soil mixing.

Soil mixing is one method of so-called *ground improvement* or *earth improvement;* these terms refer to any of a variety of methods for altering the properties of soil in place. Soil mixing, for example, can also be used to create cutoff walls to prevent water seepage into excavations, to stabilize or strengthen areas of weak soil around or under buildings, or to remediate biologically or chemically contaminated soil by adding chemicals that neutralize the contamination. Another form of ground improvement, rammed aggregate piers, is discussed later in this chapter.

Slurry Walls

A *slurry wall* is a more complex method of constructing a complete, steel-reinforced, concrete wall in the ground, even many stories below the surface, before excavation takes place. It is a relatively expensive form of excavation support that is usually economical only if it becomes part of the permanent foundation of the building. The excavation for a slurry wall is performed with a narrow *clamshell bucket*, operated by crane, and guided by temporary guides at the ground surface defining the edges of the wall (Figure 2.18). As the trench deepens, the tendency of the earth walls to collapse is counteracted by maintaining the trench full at all times with a viscous mixture of water and bentonite clay or polymers, called a *slurry*. This slurry exerts pressure against the earth walls, holding them in place.

When the trench has been excavated to its full depth, steel tubes, equal in diameter to the width of the trench, are inserted vertically at intervals to divide the trench into sections of a size that can be reinforced and concreted conveniently. Into each section, a steel cage of reinforcing steel is lowered, and concrete is poured from the bottom up, using a funnel-and-tube arrangement called a *tremie*. As the concrete rises in the trench, the slurry is displaced and

FIGURE 2.17
Soil-mixed excavation support, strong enough to support soil pressures from adjacent buildings. Excavation proceeds after the soil mixture has hardened. Bracing consists of soldier piles, walers, and tiebacks. The soldier piles are inserted during mixing, before the soil-cement mixture hardens. The walers and tiebacks are installed as excavation progresses. *(Courtesy of Schnable Foundation Company.)*

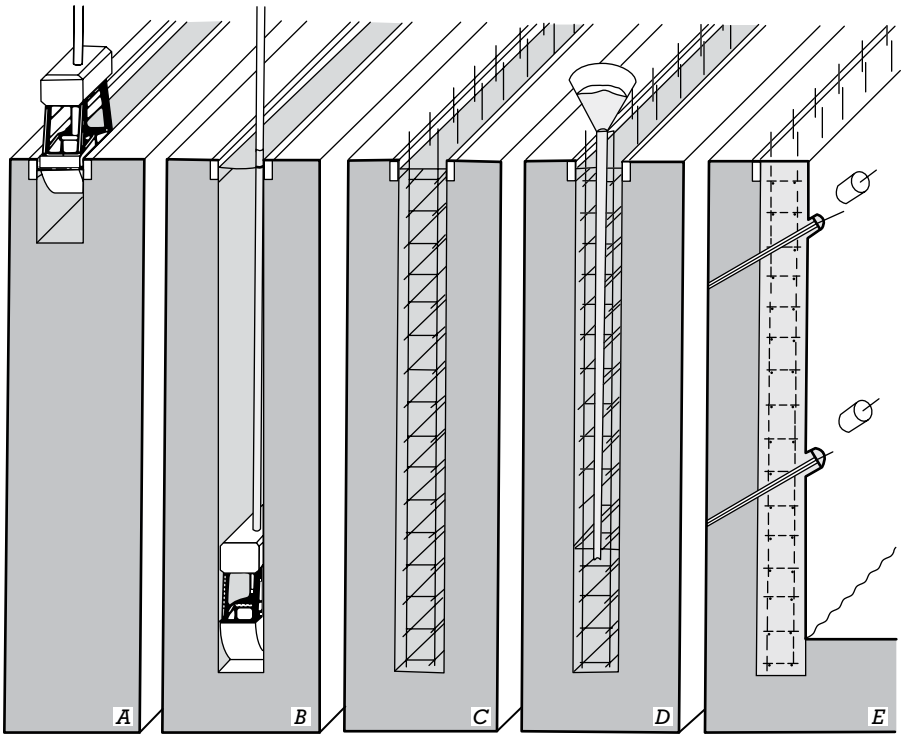


FIGURE 2.18
Steps in constructing a slurry wall. (*A*) Temporary concrete guide walls are installed at the surface, and the clamshell bucket begins excavating the trench through a bentonite clay slurry. (*B*) The trench is dug to the desired depth, with the slurry serving to prevent collapse of the walls of the trench. (*C*) A welded cage of steel reinforcing bars is lowered into the slurry. (*D*) The trench is concreted from the bottom up with the aid of a tremie. The displaced slurry is pumped from the trench, filtered, and stored for reuse. (*E*) The reinforced concrete wall is tied back as excavation progresses.

pumped out into holding tanks, where it is stored for reuse. After the concrete in one section reaches the top of the trench and has hardened, the vertical pipes on either side are withdrawn, and adjoining sections can be poured. This process is repeated until concreting of all sections of the wall is completed. When the concrete wall has cured to adequate strength, earth removal begins inside the wall, which serves as shoring for the excavation. In most cases, this wall will also become a permanent part of the future building foundation or substructure.

Slurry walls can also be constructed from precast, rather than sitecast, concrete. Prestressed wall sections are produced in a precasting plant (see Chapter 15) and then trucked to the construction site. The slurry for precast walls may include portland cement in addition to the

FIGURE 2.19
Three types of ground support used in one excavation. The uppermost portions consist of steel soldier piles and wood lagging. Middle portions are the same soldier piles, but with shotcrete lagging in place of wood. The shotcrete is stiffer and stronger than wood, and immune from decay. The lower portions of the excavation are supported with closely spaced, drilled concrete contiguous piers, with even greater capacity than either of the systems above. All three support systems are braced with tiebacks. *(Photo by Joseph Iano.)*

water and bentonite clay. Before a section is lowered by crane into the slurry, one face is coated with a release compound that will prevent the clay-cement slurry from adhering. The wall sections are installed side by side in the trench, joined by tongue-and-groove edges or synthetic rubber gaskets. After the portland cement has caused the slurry to harden, excavation begins, with the hardened slurry on the exposed face of the wall dropping away from the coated surface as soil is removed.

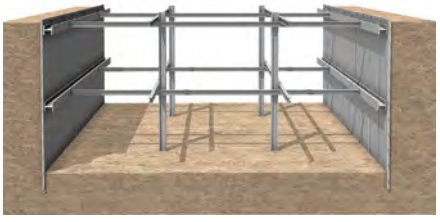
Compared to sitecast concrete, a precast concrete slurry wall can have a smoother, flatter, more attractive surface; may be thinner due to the structural efficiency of prestressing; and may have greater watertightness because of the continuous layer of solidified clay on the unexcavated side.

Contiguous Piers

Contiguous pier excavation support consists of cylindrical concrete piers spaced closely enough that they form a continuous wall, much like soil-mixed excavation support (Figure 2.19). The piers are constructed by drilling holes into the unexcavated earth, inserting steel reinforcing, and then filling the holes with concrete. Once the concrete has hardened and gained sufficient strength, excavation proceeds down one side of the piers. When the piers are spaced so that their edges just abut one another, they are also called a *tangent wall*. Or, if spaced more closely so that the piers partially overlap, they may be called a *secant wall*. Concrete piers are also used as discrete foundation elements in larger buildings, and their construction is discussed in more detail later in this chapter.

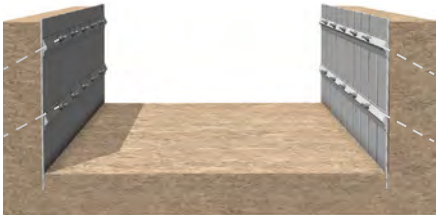
Bracing

As an excavation deepens, its support system must be braced against earth and water pressures (Figure 2.20). *Crosslot bracing* uses temporary steel wide-flange columns that are driven into the earth at points where braces will cross. As the earth is excavated down around the shoring and the columns, tiers of horizontal bracing, usually of steel, are added to support *walers*, which are beams that span across the face of the sheeting. Where the excavation is too wide for crosslot bracing, sloping *rakers* are used instead, bearing against temporary footings.



CROSSLOT BRACING

RAKERS



TIEBACKS

FIGURE 2.20
Three methods of bracing excavation support, drawn in cross section. Tiebacks are the preferred method for most large excavations, as they leave the excavation free of obstructions.

Both rakers and crosslot bracing, and especially the latter, are a hindrance to the excavation process, as their presence within the excavation places limitations on earth removal methods and equipment. Where soil conditions permit, *tiebacks* can be used instead of bracing to support the shoring while maintaining a fully open excavation. At each level of walers, holes are drilled at intervals through the shoring and the surrounding soil into rock or a stratum of stable soil. Steel cables or rods are inserted into the holes, grouted to anchor them in place, and stretched tight with hydraulic jacks (posttensioned) before they are fastened to the walers (Figures 2.21 and 2.22).

Excavation in fractured rock can often be done without any sheeting, either by injecting grout into the joints of the rock to stabilize it or by drilling into the rock and inserting *rock anchors* that fasten the blocks together (Figure 2.23).

In some cases, vertical walls of particulate soils can be stabilized by *soil nailing*. A soil nail is similar to a rock anchor. A length of steel bar is

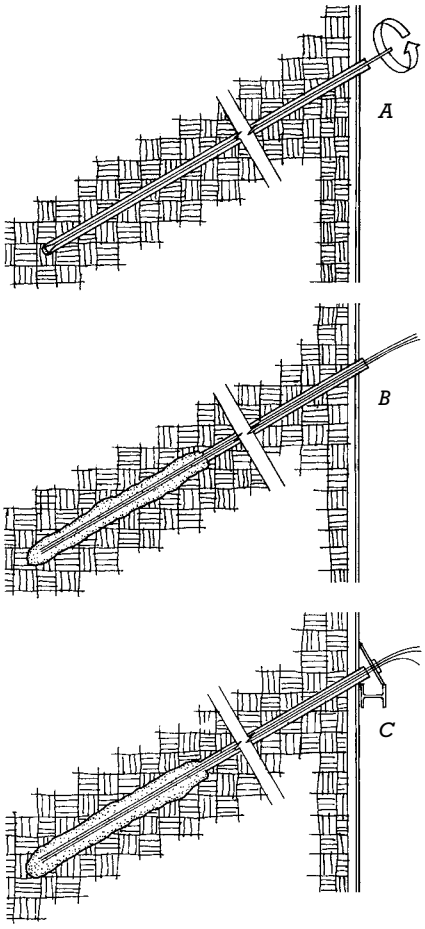


FIGURE 2.21
Three steps in the installation of a tieback to a soil anchor. (*A*) A rotary drill bores a hole through the sheeting and into stable soil or rock. A steel pipe casing keeps the hole from caving in where it passes through noncohesive soils. (*B*) Steel prestressing tendons are inserted into the hole and grouted under pressure to anchor them to the soil. (*C*) After the grout has hardened, the tendons are tensioned with a hydraulic jack and anchored to a waler.

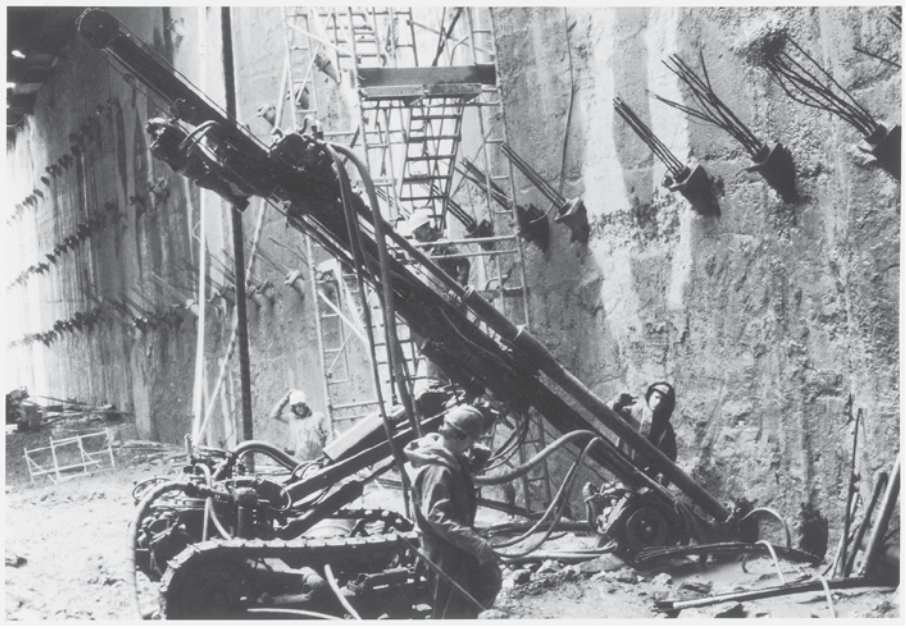


FIGURE 2.22
Drilling through a slurry wall for a tieback. The ends of hundreds of completed tiebacks protrude from the wall. *(Courtesy of Franki Foundation Company.)*

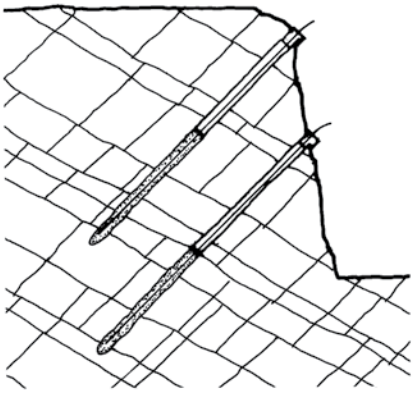


FIGURE 2.23
Rock anchors are similar to tiebacks but are used to hold jointed rock formations in place around an excavation.

inserted into a nearly horizontal hole drilled deep into the soil. Grout is injected into the hole to bind the nail to the surrounding soil. Large numbers of closely spaced nails are used to knit a large block of soil together so that it behaves more like weak rock than particulate soil.

Bracing and tiebacks in excavations are usually temporary. Their function is eventually taken over by the floor structure of the basement levels of the building, which is designed to resist the lateral loads from the surrounding earth acting on the substructure walls.

Dewatering

During construction, excavations must be kept free of standing water from precipitation or groundwater seepage. Some shallow excavations in relatively dry soils may remain free of water without any intervention. But most excavations require some form of *dewatering*, or removal of water from the excavation or surrounding soil. The most common method of dewatering is by pumping as the water accumulates in pits, called *sumps*, located at low points in the excavation.

Where the volume of groundwater flowing into the excavation is great, or with soils, such as sand or silt, that may be softened by constant seepage, it may be necessary to keep groundwater from entering the excavation at all. This can be done either by pumping water from the surrounding soil to depress the water table below the bottom of the excavation or by erecting a watertight barrier around the excavation (Figure 2.24).

Well points are used to depress the water table. These are vertical pipes inserted into the ground with screened openings at the bottom that keep out soil particles while allowing water to enter. Closely spaced well points are driven into the soil around the perimeter of the excavation and connected to pumps that continually draw water from the ground and discharge it away from the building site. Once pumping has drawn down the water table in the area of the excavation, work can proceed "in the dry" (Figure 2.25). Suction pumps stationed at ground level can only draw water from a depth of about 18 to 20 feet (5.5 to 6.1 m). For deeper excavations, two or more rings of well points may be required, the inner rings working at deeper levels than the outer ones. Or, a single ring of deep wells with submersible pumps at their bottoms may be installed.

Well points are not always practical: They may have insufficient capacity to keep the excavation dry, restrictions on the discharge of groundwater may preclude their use, or lack of reliability due to power outages may be a concern. In some locations, lowering of the water table could adversely affect neighboring buildings, causing soil consolidation under their foundations or exposing wood foundation piles, previously protected by immersion in water, to decay once they come in contact with air. In these cases, a *watertight barrier wall* or *cutoff wall* made from sheet piling, a slurry wall, soil-mixed wall, or contiguous piers may be used (Figure 2.24). *Soil freezing* is also possible. With this strategy, an array of vertical pipes similar to well points is used to circulate coolant at temperatures low enough to freeze the soil around an excavation area, resulting in a temporary but reliable barrier to groundwater. Watertight barriers must resist the hydrostatic pressure of the surrounding water, which increases with depth, so for deeper excavations, a system of bracing or tiebacks is required. A watertight barrier also works only if it reaches into a stratum of impermeable soil at its bottom, such as bedrock or water-impermeable clay. Otherwise, water can flow underneath the barrier and rise up from the bottom of the excavation.

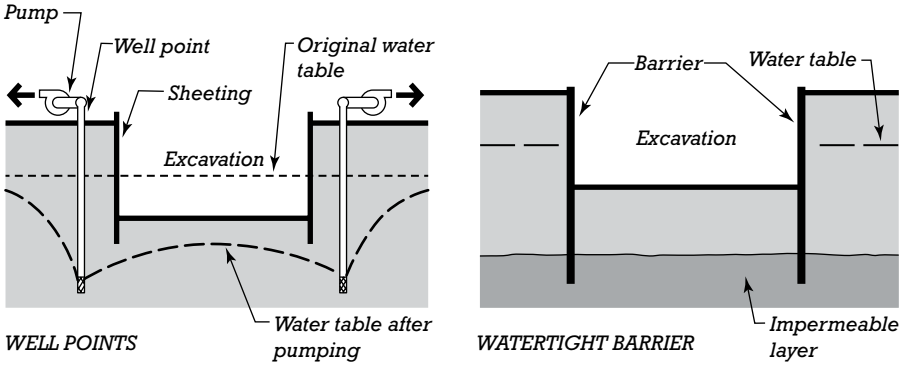


FIGURE 2.24
Two methods of keeping an excavation dry, viewed in cross section. The water sucked from well points depresses the water table in the immediate vicinity to a level below the bottom of the excavation. Watertight barrier walls work only if their bottom edges are inserted into an impermeable stratum that prevents water from working its way under the walls.

FIGURE 2.25
Well point dewatering. The pump at right draws water from well points through the larger-diameter white, plastic pipe called the header. Well point connections, spaced roughly every 6 feet (1.8 m), are made along the top of the header. Water is discharged from the pump through the black flexible hose, which, through additional piping, leads to a settlement tank (far left in the photo) where soil particles are captured. From there, the clear water is discharged to the municipal sewer system. *(Photo by Joseph Iano.)*

FOUNDATIONS

It is convenient to think of a building as consisting of three major parts: the *superstructure*, the above-ground portion of the building; the *substructure*, the habitable portion below ground; and the foundations, the below-ground components of the building devoted solely to the transfer of loads into the soil (Figure 2.26).

There are two basic types of foundations: shallow and deep. *Shallow foundations* transfer building loads to the earth close to the base of the substructure. *Deep foundations*, either piles or caissons, extend downward through layers of weak or unstable strata to reach more competent soil or rock deeper within the earth. Shallow foundations are less expensive than deep ones and are used wherever possible.

The best choice of foundation type for any particular building is sometimes obvious, especially where shallow foundations will work. In other cases, in-depth investigation and evaluation may be required to determine the optimal design. Subsurface soil types, groundwater conditions, and the structural requirements

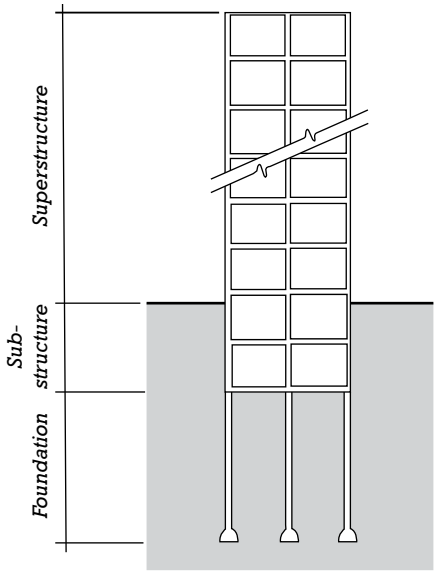


FIGURE 2.26
Superstructure, substructure, and foundation. The substructure in this example contains two basement levels, and the foundation consists of bell caissons. (In some buildings, the substructure and foundation may be partly or wholly the same.)

of the superstructure are primary considerations. Additionally, local construction practices; environmental considerations of noise, traffic, and disposal of earth materials and water; potential impacts on adjacent properties; construction schedules; and other considerations may come into play.

Shallow Foundations

Spread Footings

Most shallow foundations are simple concrete *spread footings*. Spread footings take concentrated loads from above and spread them out across an area of soil large enough that a safe soil pressure is not exceeded. A *column footing* is a square block of concrete, with or without steel reinforcing, that distributes a column load to the soil below. A *wall footing*, or *strip footing*, is a continuous strip of concrete that serves the same function for a load-bearing wall (Figures 2.27 and 2.28).

To minimize settlement, spread footings must be placed on undisturbed soil. Alternatively, where there are areas of unsuitable soil at the bearing level, native soil may be removed and replaced with *engineered fill*, properly formulated higher-strength, more stable soil material brought from offsite. This material is placed in layers and compacted to a specified density, usually under

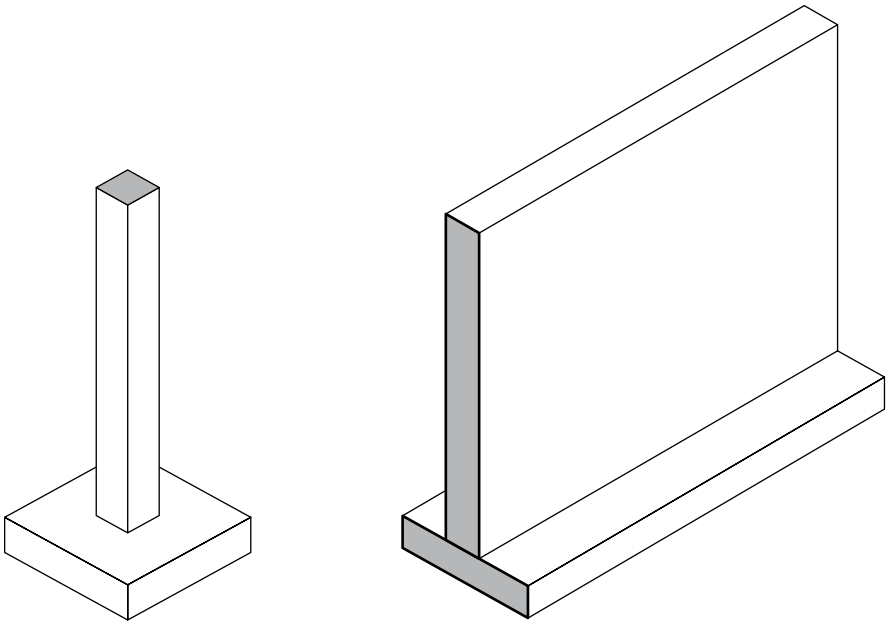


FIGURE 2.27
A column footing and a wall footing of concrete. The steel reinforcing bars have been omitted from this illustration for clarity. The role of steel reinforcing in concrete elements is explained in Chapter 13.

Interactive Exercise

FIGURE 2.28
Concrete foundation walls and footings. Where a column will land, the footing is widened. In the foreground are protruding steel reinforcing bars with protective caps. These bars will add shear strength (resistance to sliding) to the connection between the footing and the concrete wall that will be poured on top of it. *(Photo by Joseph Iano.)*

the supervision of a soils engineer, to ensure that the required loadbearing capacity and stability are achieved.

In cold climates, footings must also be placed below the *frost line*, the level to which the ground freezes in winter. Foundations exposed to freezing temperatures can be lifted and damaged by soil that expands as it freezes or by *ice lenses*, thick layers of ice that form as water vapor migrates upward from the soil and is trapped under the footing.

In climates with little or no ground freezing, the thickened edges of a concrete *slab on grade* (see Chapter 14 for further information on slabs on grade) can function as simple, inexpensive spread footings for one- and two-story buildings. Where footings must be deeper, or where floors are raised over a *crawlspace* or *basement*, concrete or masonry walls resting on strip footings provide support for the

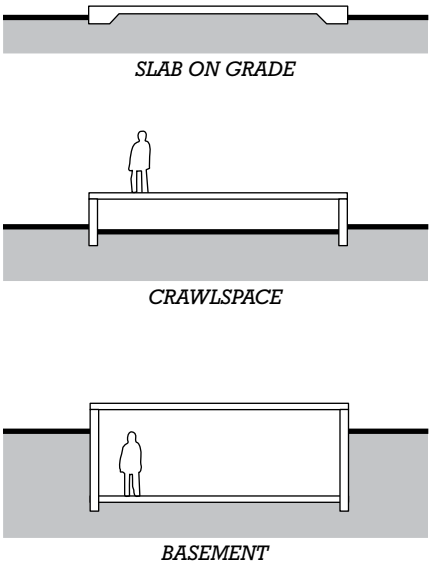


FIGURE 2.29
Three types of substructures with shallow foundations. The slab on grade is the most economical under many circumstances. A crawlspace is used under a raised floor structure and gives easier access to underfloor piping and wiring than a slab on grade. Basements provide usable space.

structure above (Figure 2.29). When building on slopes, strip footings are stepped to maintain the required depth of footing at all points around the building (Figure 2.30). If a sloping site or earthquake precautions require it, column footings may be linked together with reinforced concrete *tie beams* or grade beams to maintain stability of the footings when subjected to lateral forces.

Footings cannot legally extend beyond a property line, even for a building built tightly to that line. If the outer toe of the footing were simply cut off at the property line, the footing would be unbalanced by the off-center column or wall above and tend to rotate and fail. *Combined footings* and *cantilever footings* solve this problem by tying the footings for the outside row of columns to those of the next row in such a way that any imbalance is neutralized (Figure 2.31).

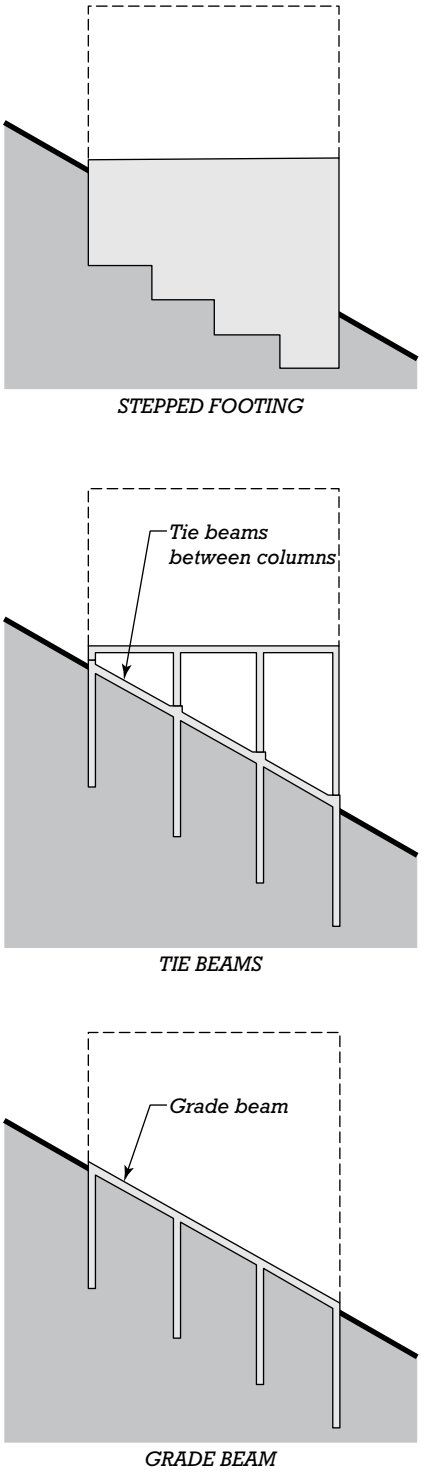


FIGURE 2.30
Foundations on sloping sites, viewed in a cross section through the building. The broken line indicates the outline of the superstructure. Wall footings are stepped to maintain the necessary distance between the bottom of the footing and the surface of the ground. Separate column foundations, whether caissons (as shown here) or column footings, are often connected with reinforced concrete tie beams to reduce differential movement between the columns. Grade beams, discussed further later in this chapter, differ from tie beams by being reinforced to distribute the continuous load from a bearing wall above to separate foundation elements below.

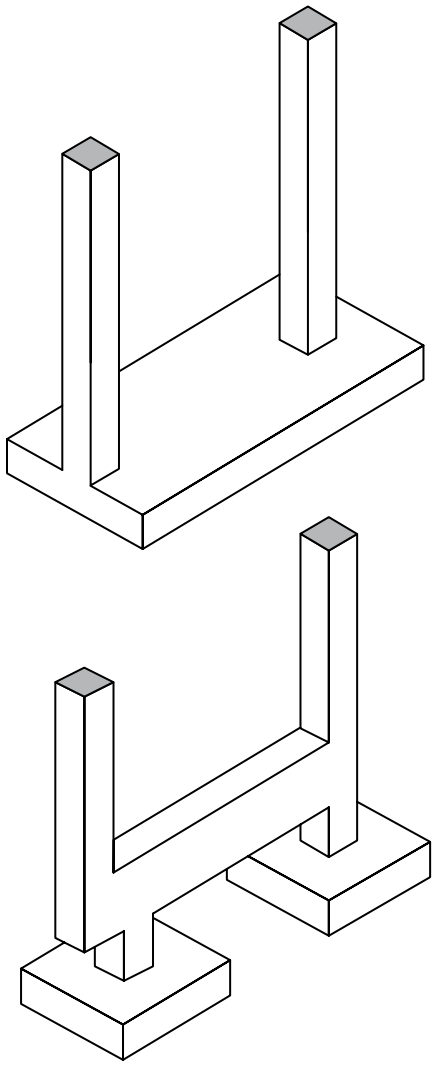


FIGURE 2.31
Either a combined footing (*top*) or a cantilevered footing (*bottom*) is used when columns must abut a property line. By combining the foundation for the column against the property line, at the left, with the foundation for the next interior column to the right in a single structural unit, a balanced footing design can be achieved. The concrete reinforcing steel has been omitted from these drawings for the sake of clarity.

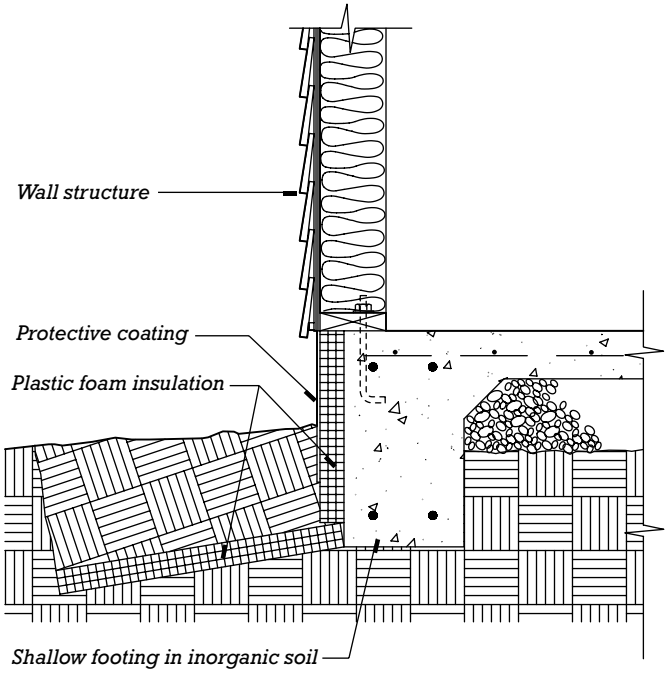


FIGURE 2.32
A typical detail for a shallow frost-protected footing.

Shallow Frost-Protected Foundations

Where the frost line is deep, excavation costs can be saved by constructing *shallow frost-protected foundations*. These are footings placed closer to the ground surface, but insulated in such a way that the ground underneath them cannot freeze. Continuous layers of insulation board are placed around the perimeter of the building in such a way that heat flowing into the soil in winter from the interior of the building maintains the soil beneath the footings at a temperature above freezing (Figure 2.32). Even beneath unheated buildings, properly installed thermal insulation can trap enough geothermal heat around shallow foundations to prevent freezing. The insulation boards for shallow frost-protected footings are made from foam plastic or other material that can withstand the effects of ground moisture and earth pressures.

Mat Foundations

In situations where the bearing capacity of the soil is low in relation to building loads, column footings may become so closely spaced that it is more effective to merge them into a single *mat* (*raft*) *foundation* that supports the entire building. Mat foundations for very tall buildings are heavily reinforced and may be 6 feet (1.8 m) or more in thickness (Figure 2.33).

A *floating* (*compensated*) *foundation* is a special type of mat footing. It is a mat foundation placed at a depth such that the weight of the soil removed from the excavation is close to the weight of the building constructed above. In this way, the load on the underlying soil changes very little, and settlement is minimized. As a rule of thumb, one story of excavated soil weighs about the same as five to eight stories of superstructure, depending on the density of the soil and the construction of the building (Figure 2.34). A compensated foundation for a 30-story building, therefore, would require an excavation four to six stories deep to achieve the necessary balance between removed soil and imposed building load.

Deep Foundations

Caissons

A *caisson*, or *drilled pier* (Figure 2.35), is similar to a column footing in that it spreads the load from a column over a large enough area of soil that the allowable pressure in the soil is not exceeded. It differs from a column footing in that it extends through strata of unsatisfactory soil beneath the substructure of a building until it reaches a more suitable stratum.

A caisson is constructed by drilling a hole, *belling* (flaring) the hole out at the bottom as necessary to achieve the required bearing area, and filling the hole with concrete. Large *auger drills* (Figures 2.36 and 2.37) are used for drilling caissons. Occasionally hand excavation is used where the soil is too full of boulders to drill. Depending on soil conditions, the soil around the drilled hole may be temporarily supported with a cylindrical steel casing lowered around the drill as it progresses, or by temporarily filling the hole with water or a slurry, similar to slurry wall construction. When a firm bearing stratum is reached, the bell, if required, is created at the bottom of the shaft either by hand excavation or, more commonly, by a special *belling bucket* on the drill (Figure 2.38). The bearing surface of the soil at the bottom of the hole is then inspected to be sure it is of the anticipated quality. Finally, the hole is filled with concrete, with any temporary casing withdrawn or water or slurry pumped out as the concrete rises. Reinforcing is seldom used in the concrete except near the top of the caisson, where it joins the building structure above.

Caissons are large, heavy-duty foundation components (Figure 2.39). Their shaft diameters range from 18 inches (460 mm) up to 12 feet (3.6 m) or more. *Belled caissons* are practical only where the bell can be excavated in a cohesive soil that will retain its shape at least until the concrete is poured. Where groundwater is present, the temporary steel casing can prevent

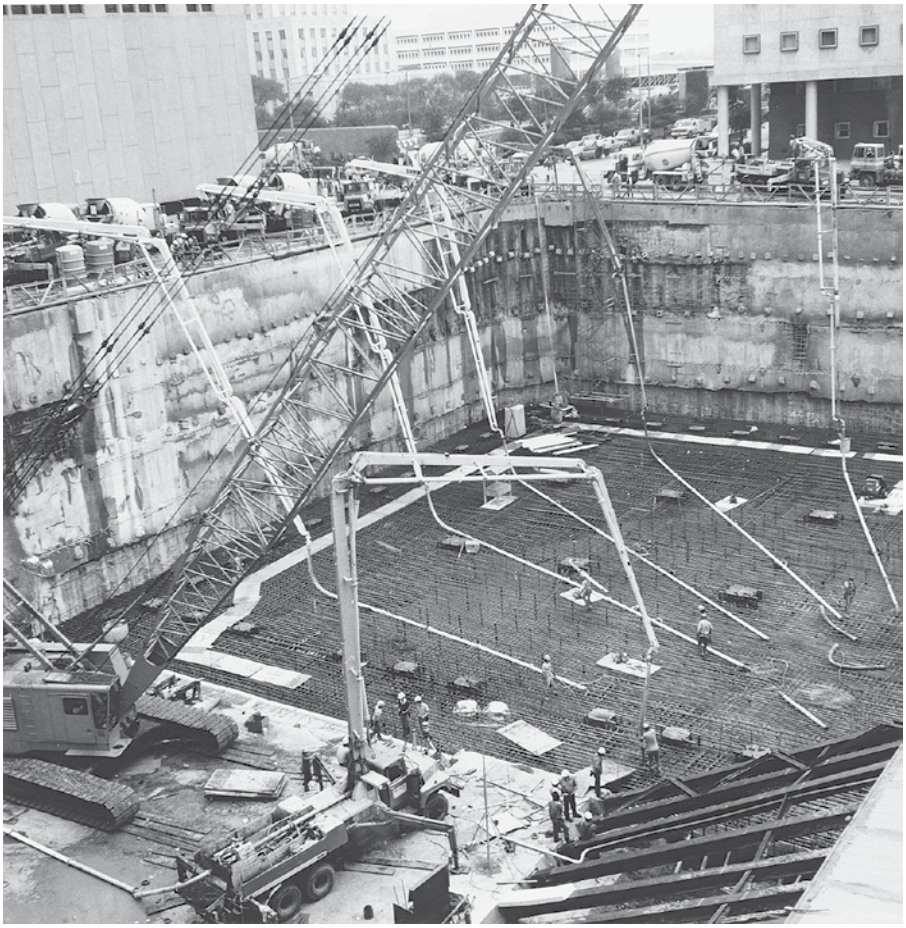


Figure 2.33
Pouring a large foundation mat. Six truck-mounted pumps receive concrete from a continuous procession of transit-mix concrete trucks and deliver this concrete to the reinforced mat. Concrete placement continues nonstop around the clock until the mat is finished, to avoid "cold joints," which are weakened planes between hardened concrete and fresh concrete. The soil around this excavation is supported with a sitecast concrete slurry wall. Most of the slurry wall is tied back, but a set of rakers is visible at the lower right. *(Courtesy of Schwing America, Inc.)*

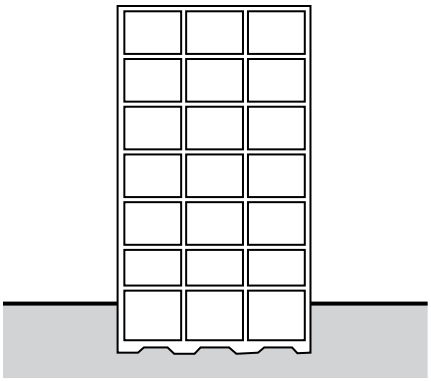


Figure 2.34
A cross section through a building with a floating foundation. The building weighs approximately the same as the soil excavated for the substructure, so the stress in the soil beneath the building is the same after construction as it was before.

Figure 2.35
Deep foundations. Caissons are concrete cylinders poured into drilled holes. They reach through weaker soil (light shading) to bear on competent soil beneath. The end bearing caisson at the left is belled as shown when additional bearing capacity is required. The *socketed caisson* **is drilled into a hard stratum and transfers its load primarily by friction between the soil or rock and the sides of the caisson. Piles are driven into the earth. End bearing piles act in the same way as caissons. The friction pile derives its load-carrying capacity from friction between the soil and the sides of the pile.**

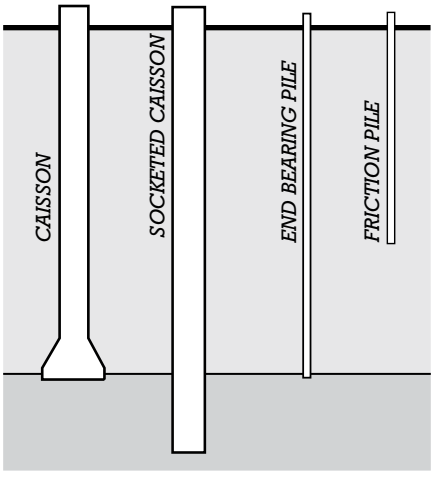


FIGURE 2.36
A 6-foot- (1828-mm-) diameter auger on a telescoping 70-foot (21-m) bar brings up a load of soil from a caisson hole. The auger will be rotated rapidly to spin off the soil before being reinserted in the hole. *(Courtesy of Calweld Inc.)*

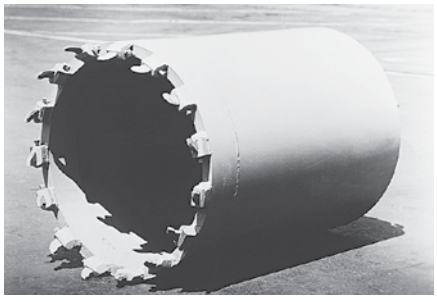


FIGURE 2.37
For cutting through hard material, the caisson drill is equipped with a carbide-toothed cutting head. *(Courtesy of Calweld Inc.)*

FIGURE 2.38
The bell is formed at the bottom of the caisson shaft by a belling bucket with retractable cutters. The example shown here is for an 8-foot- (2.44-m-) diameter shaft and makes a bell 21 feet (6.40 m) in diameter. *(Courtesy of Calweld Inc.)*

FIGURE 2.39
Caisson drilling in progress. On the left half of the image, a number of temporary steel casings have already been installed. The ends of the cylinders are flanged so that they can be coupled to make longer sections as the drilling proceeds. In the center of the image, the tracked rotary drilling rig manipulates two major parts. Suspended just above the left track is the bucket barrel that fits within the steel casings and is used to extract soil as the casing is advanced. Above the bucket is the larger-diameter casing twister that engages with tabs in the tops of the steel cylinders and drives the cylinders into the soil. Once the cylinders have reached the required depth, steel-reinforcing cages are inserted, and as concrete is poured, the cylinders are then extracted for reuse. *(Photo by Joseph Iano.)*

flooding of the caisson hole during its construction. But where the bearing stratum is permeable, water may fill the hole from below and caisson construction may not be practical.

Piles

Piles (Figure 2.35) are more slender than caissons, and usually forcibly driven into the earth rather than drilled and poured. They are used where noncohesive soils, subsurface water, or excessive depth of bearing strata make caissons impractical. If a pile is driven until its tip encounters firm resistance from a suitable bearing stratum such as rock, dense sands, or gravels, it is an *end bearing pile*. If no firm bearing layer can be reached, a pile may still develop a considerable load-carrying capacity through frictional resistance between the sides of the pile and the soil through which it is driven; in this case, it is known as a *friction pile*. (Often piles rely to some degree on a combination of end bearing and friction for their strength.) Piles are usually driven closely together in clusters that contain 2 to 25 piles each. The piles in each cluster are later joined at the top by a reinforced concrete *pile cap*, which distributes the load of the column or wall above among the piles (Figures 2.40 and 2.41).

If . . . solid ground cannot be found, but the place proves to be nothing but a heap of loose earth to the very bottom, or a marsh, then it must be dug up and cleared out and set with piles made of charred alder or olive wood or oak, and these must be driven down by machinery, very closely together.

—Marcus Vitruvius Pollio (Roman architect), *The Ten Books on Architecture*, 1st century BC

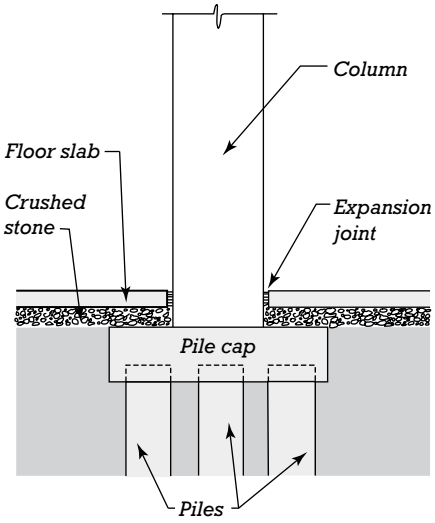


FIGURE 2.40
An elevation view of a pile cap, column, and floor slab. Pile caps are reinforced to transmit column loads equally into all the piles in the cluster, but the reinforcing steel has been omitted here for the sake of clarity.

End bearing piles work essentially the same as caissons and are used on sites where a firm bearing stratum can be reached, even sometimes at depths of 150 feet (45 m) or more. Each pile is *driven to refusal*, the point at which little additional penetration is made with continuing blows of the hammer, indicating that the pile is firmly embedded in the bearing layer. Friction piles are driven either to a predetermined depth or until a certain level of resistance to hammer blows is encountered, rather than to refusal as with end bearing piles. Clusters of friction piles have the effect of distributing a concentrated load from the structure above into a large volume of soil around and below the cluster, at stresses that lie safely within the capacity of the soil (Figure 2.42). The loadbearing capacities of piles are calculated in advance based on soil test results and the properties of the piles. To verify these calculations, as well as to determine the rate and ease with which piles can be installed, test piles are often driven and loaded on the building site before foundation work begins.

Where piles are used to support loadbearing walls, reinforced concrete *grade beams* are constructed between the pile caps to transmit the wall loads to the piles (Figure 2.43). Grade beams are also used with caisson foundations for the same purpose.

Pile Driving

Conventional piles are driven with *pile hammers*, heavy weights lifted by the energy of steam, compressed air, compressed hydraulic fluid, or diesel fuel combustion, then dropped on the top of the pile. The *piledriver* includes additional hoisting machinery for raising the piles themselves into position before driving (Figure 2.44).

In certain types of soil, piles can be driven more efficiently by vibration than by hammer blows alone, using a vibratory hammer mechanism. Also, as discussed later in this chapter, some lightweight pile systems are installed by rotary drilling or hydraulic pressing.

Pile Materials

Piles may be made of wood, steel, concrete, or various combinations of these materials (Figure 2.45). The simplest are *timber piles*, made from tree trunks with their branches and bark removed and driven into the ground small end first. Timber piles have been used since Roman times, when they were driven by large hammers hoisted by muscle power. Their main advantage is that they are economical for lightly loaded foundations. A primary disadvantage is that they cannot be spliced during driving and are, therefore, limited to the length of available tree trunks, or approximately 65 feet (20 m). Unless pressure treated with a chemical preservative or completely submerged

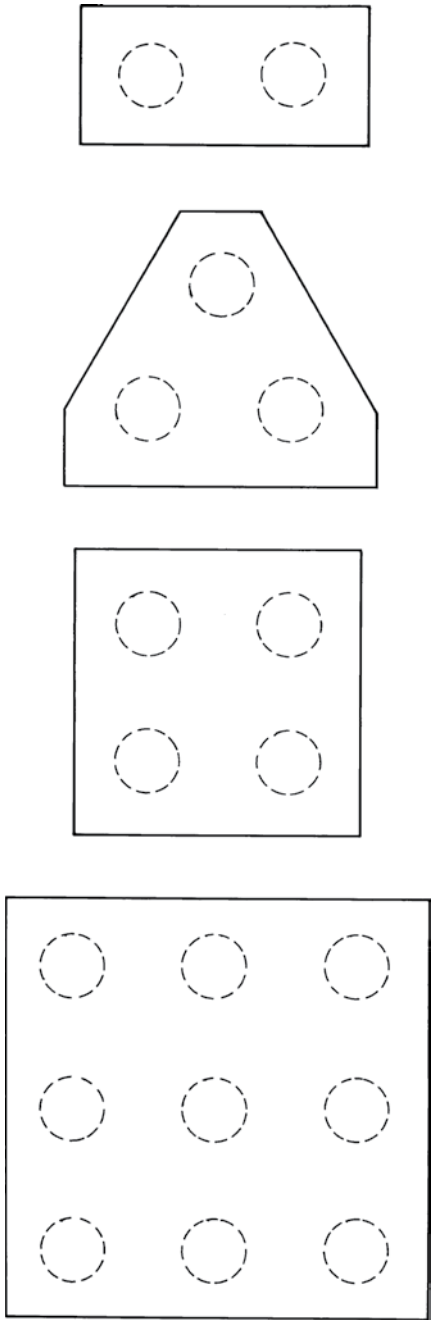


FIGURE 2.41
Clusters of two, three, four, and nine piles with their concrete caps, viewed from above.

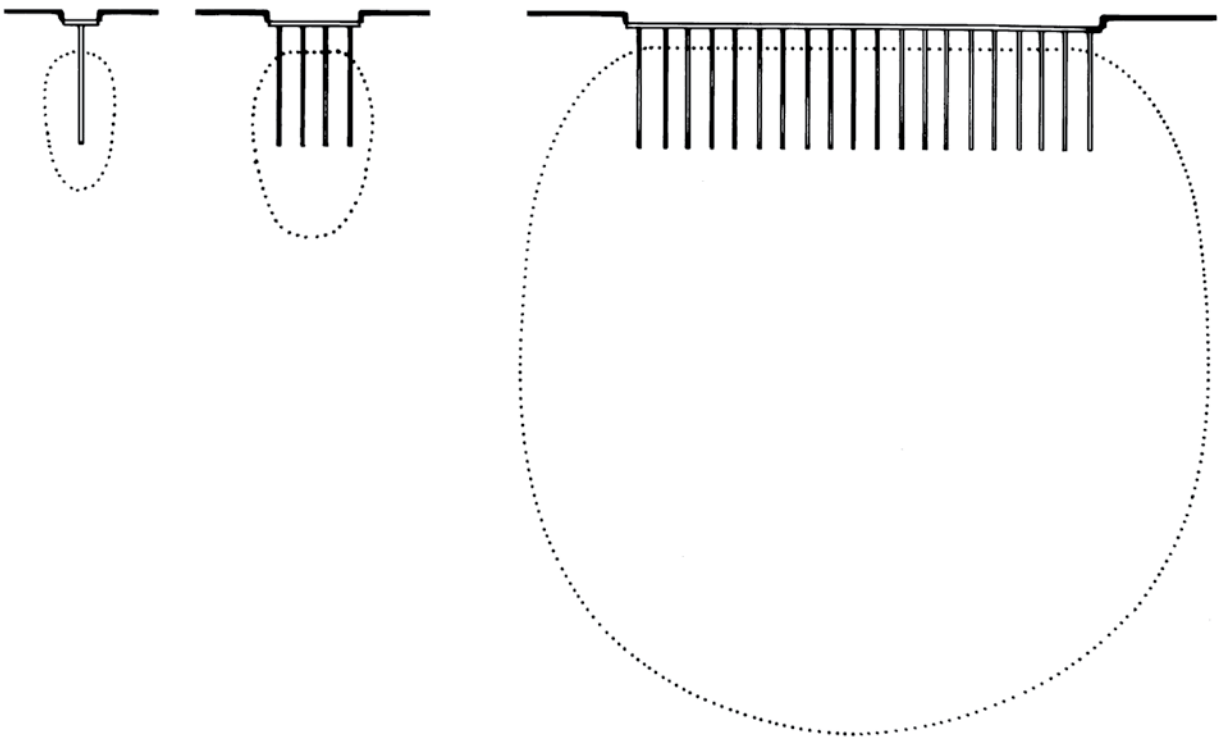


FIGURE 2.42
A single friction pile (*left*) transmits its load into the earth as an equal shear pressure along the bulb profile indicated by the dotted line. As the size of the pile cluster increases, the piles act together to create a single larger bulb of higher pressure that reaches deeper into the ground. A building with many closely spaced clusters of piles (*right*) creates a very large, deep bulb. Care must be taken to ensure that large-pressure bulbs do not overstress the soil or cause excessive settlement of the foundation. The settlement of a large group of friction piles in clay, for example, will be considerably greater than that of a single isolated pile.

below the water table, they will decay (the lack of free oxygen in the water prohibits the organic growth that causes wood decay). Relatively small hammers must be used when driving timber piles, to avoid splitting the piles. Capacities of individual timber piles lie in the range of 10 to 55 tons (90 to 490 kN).

Steel piles made be made from H-sections or pipes. H-piles are special wide-flange sections (see Chapter 11), 8 to 18 inches (200 to 460 mm) deep, which are approximately square in cross section. They are used in end bearing applications. H-piles displace relatively little soil during driving. This minimizes the upward displacement of adjacent soil, called *heaving*, that may occur with other pile types. Soil displacement can be a problem on urban sites, where it can disturb adjacent buildings.

H-piles can be brought to the site in any convenient lengths, welded together as driving progresses to form any necessary length of pile, and cut off with an oxyacetylene torch when the required depth is reached. The cutoff ends can then be welded onto other piles to avoid waste. Corrosion can be a problem in some soils, however, and unlike closed-pipe piles and hollow precast concrete piles, H-piles cannot be inspected after driving to be sure they are straight and undamaged.

Steel *pipe piles* have diameters of 8 to 24 inches (200 to 600 mm) or more. The lower, driven end of the pipe may be either open or closed. An open pile is easier to drive than a closed pile and, depending on soil conditions, may displace less soil. After driving, the pipe is cleared of soil, inspected to ensure that it is straight and undamaged, and then filled with concrete. A closed pile can be inspected and concreted immediately after driving. Pipe piles generally displace larger amounts of soil during driving than H-piles, increasing the possibility of upward heaving of nearby soil and disturbance of nearby buildings. The larger sizes of pipe piles require a heavier hammer for driving as well. H-piles and steel pipe piles can carry loads up to approximately 200 to 300 tons (1800 to 2700 kN).

Conventional steel piles normally have no added corrosion protection. The low levels of free oxygen in undisturbed soils generally limit corrosion to rates that can be accounted for in the thickness of the steel sections themselves. Or, where soil conditions are unusually severe, a concrete pile may chosen instead.

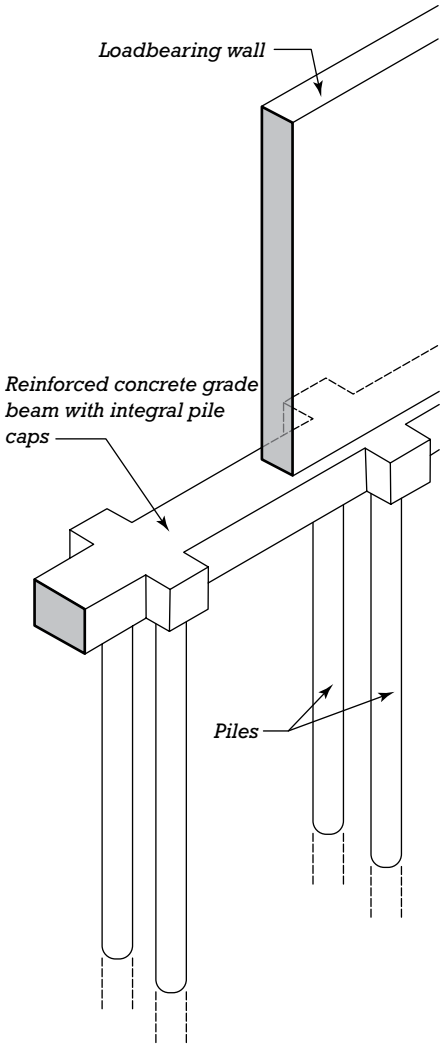
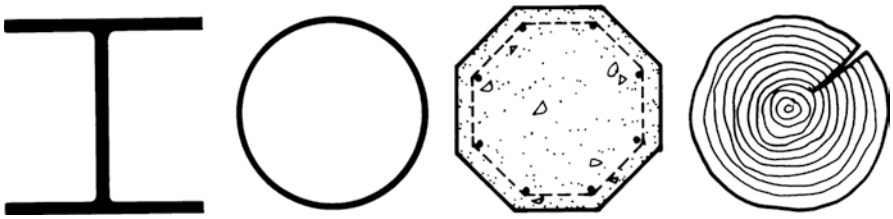


FIGURE 2.43
To support a loadbearing wall, pile caps are joined by a grade beam. The reinforcing in the grade beam is similar to that in any ordinary continuous concrete beam and has been omitted for clarity. In some cases, a concrete loadbearing wall can be reinforced to act as its own grade beam.

FIGURE 2.44
A piledriver hammers a precast concrete pile into the ground. The heavy diesel piston hammer is guided on a vertical rail called a lead (pronounced "leed"). The hammer follows the pile down the leads as the pile progresses deeper into the soil. *(Photo by Joseph Iano.)*



STEEL H-PILE *STEEL PIPE PILE* *PRECAST CONCRETE PILE* *WOOD PILE*

FIGURE 2.45
Cross sections of common types of piles. Precast concrete piles may be square or round instead of the octagonal section shown here and may be hollow in the larger sizes.

Minipiles, also called *pin piles* or *micropiles*, are made from steel bar or pipe 2 to 12 inches (50 to 300 mm) in diameter. They are pressed or rammed into holes drilled in the soil and then grouted in place. Where vertical space is limited, such as when working in the basement of an existing building, minipiles can be installed in individual sections as short as 3 feet (1 m) that are coupled end-to-end as driving progresses. *Helical piles*, or *screw piles*, are similar to minipiles, but with one or more helical boring blades, up to 24 inches (600 mm) in diameter, attached (Figure 2.46). A helical pile is installed by rotation, causing it to auger into the ground without predrilling.

Minipiles and helical piles are installed without hammering, thereby avoiding much of the vibration and noise associated with conventional pile installation. This makes these pile types good choices for work close to existing buildings or for the improvement of existing foundations where excessive vibration could damage structures or noise could disrupt ongoing activities. Because of their slenderness, their installation also entails little or no soil displacement, minimizing the risk of disturbance to nearby foundations. Bearing capacity for minipiles and helical piles ranges from as little as 2 tons (18 kN) to as much as 200 tons (1800 kN). (See Figure 2.52 for an illustration of minipiles used to reinforce or underpin an existing foundation.) Larger-capacity drilled minipiles, using pipes with diameters up to 24 inches (610 mm), blur the distinction between traditional piles and caissons while retaining the advantages of low-vibration installation and ability to be installed in confined spaces.

Minipiles and helical piles, being thinner in section than conventional steel piles, sometimes require added corrosion protection. For minipiles, the surrounding grouting is usually adequate. Ungrouted helical piles and minipiles may be galvanized (zinc-coated) or coated with plastic or epoxy.

Precast concrete piles are square, octagonal, or round in section, and in large sizes may have open cores to allow for inspection after driving (Figure 2.47). Most are prestressed, but some for smaller buildings may be only conventionally reinforced (for an explanation of concrete reinforcing and prestressing, see Chapter 13). Typical cross-sectional dimensions range from 10 to 30 inches (250 to 800 mm). Advantages of precast concrete piles include high load capacity and freedom from corrosion or decay.

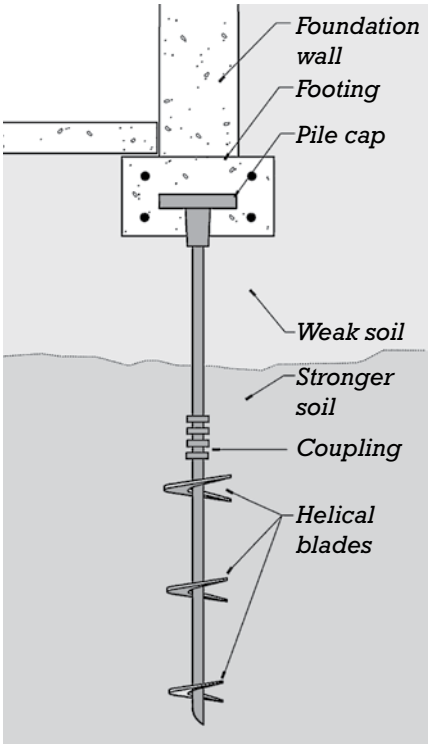


FIGURE 2.46
A helical pile. Rows of piles transfer loads from the shallow footing, located in a relatively weak soil (lighter in tone in the illustration), into the stronger underlying stratum (darker tone in the illustration).

FIGURE 2.47
Precast, prestressed concrete piles. Lifting loops are cast into the sides of the piles as crane attachments for hoisting them into a vertical position. In the background can be seen driven piles, ready for cutting off and capping. *(Courtesy of Lone Star/San-Vel Concrete.)*

Precast piles must be handled carefully to avoid bending and cracking before installation. Splices between lengths of precast piling can be made with mechanical fastening devices that are cast into the ends of the sections. Bearing capacities range up to approximately 500 tons (4400 kN).

Sitecast concrete piles are usually installed by driving a hollow steel shell into the ground and then filling the shell with concrete. The shell may remain in place as part of the finished pile, or it may be removed and reused for the installation of subsequent piles (Figure 2.48). When left in place, the shell may be corrugated to increase its stiffness. Alternatively, an auger with a hollow stem may be used to drill the hole for the pile; then concrete is deposited through the stem as the auger is withdrawn. Load capacities for sitecast concrete piles range up to approximately 200 tons (1800 kN).

In a concrete *pressure-injected footing*, or *compaction-grouted footing*, a dry, stiff mixture of concrete or grout is compacted into a predrilled hole. The compaction of the concrete or grout in place also densifies and strengthens the surrounding soil. *Rammed aggregate piers*, or *stone columns*, are similar but are constructed solely with crushed rock (Figure 2.49). Like soil mixing, these types of foundation elements are a form of ground improvement. When used for foundation work, arrays of such piers are installed to improve the structural properties of soil relatively close to the ground surface. This permits shallow, less expensive foundations to be constructed above the improved soil, in place of the deeper and more expensive foundation types that would otherwise be required. These pier types can also be used to reduce the risk of liquefaction in soils prone to this behavior, for slope stabilization, and for other types of soil strengthening.

Seismic Base Isolation

In areas where very strong earthquakes are common, large buildings may be placed on *base isolators*. When significant ground movement occurs, the base isolators flex or yield to absorb a significant portion of this movement. As a result, movement of the building structure is lessened, and the magnitude of the forces acting on the structure and the potential for damage are reduced. One type of base isolator consists of a multilayered sandwich of rubber and steel plates (Figure 2.50). When subjected to lateral forces, yielding of the rubber layers allows the isolator to deform. A lead core provides damping action and keeps the layers of the sandwich aligned.

Underpinning

Underpinning is the strengthening and stabilizing of an existing foundation. It may be required where the original foundation design proves inadequate, when a change in use or increase in building size increases the loads on an existing foundation, or when new nearby construction disturbs the soil around an existing foundation and requires that

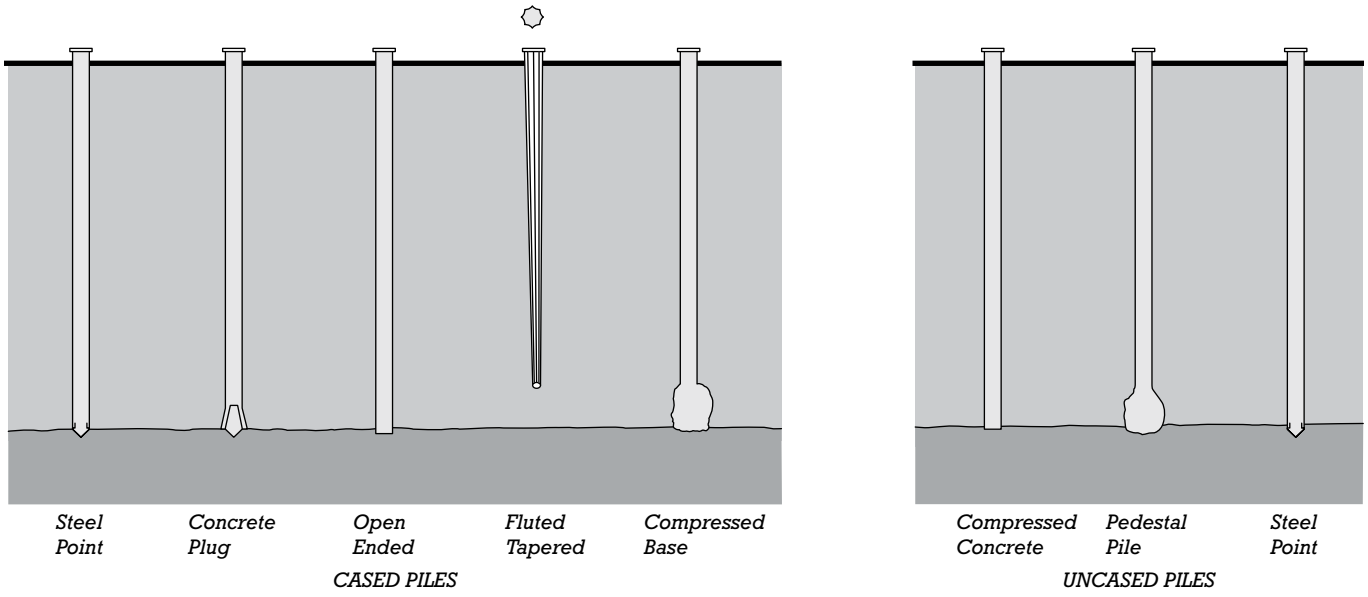
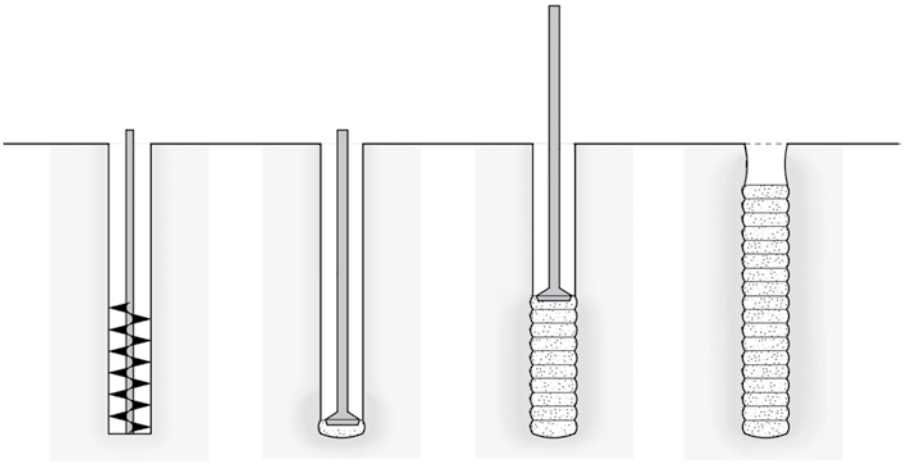
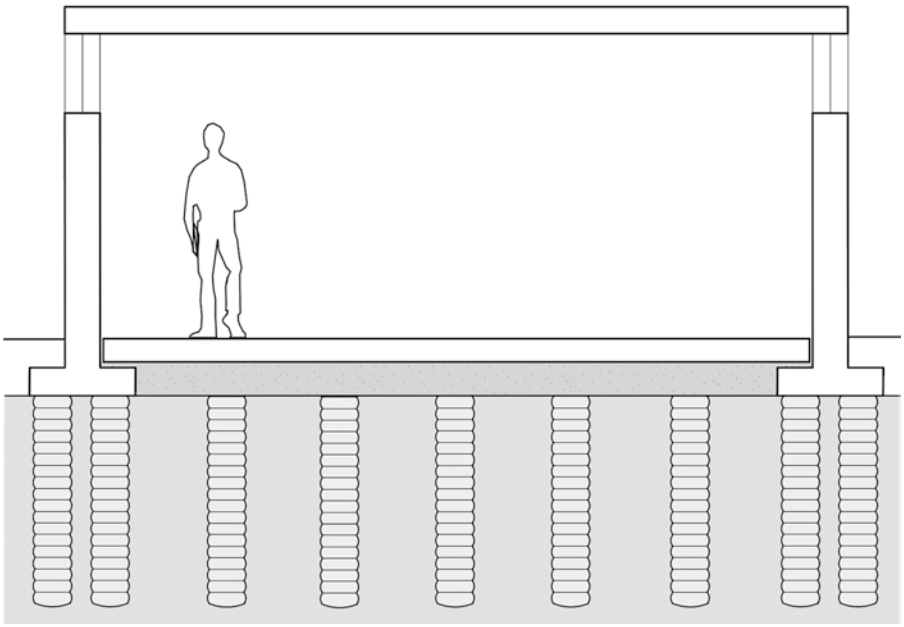


FIGURE 2.48

Various types of sitecast concrete piles. Most are cast into steel casings that have been driven into the ground. The uncased piles are made by withdrawing the casing as the concrete is poured and saving it for subsequent reuse. (Compared to steel pipe piles, the metal shells in cased concrete piles are thinner and contribute less to the bearing capacity of the pile.)



STEPS IN AGGREGATE PIER INSTALLATION



SECTION

FIGURE 2.49
Above, four steps in the construction of rammed aggregate piers. *From left to right*: (1) The pier hole is drilled with a rotating auger or high-energy vibrating probe. (2) The first lift of aggregate is compacted at the base of the hole. (3) Succeeding lifts are compacted one after the other. As lifts are compacted in place, the surrounding soil is also densified. (4) The pier is completed. Below, a diagrammatic section illustrating shallow spread footings and a slab on grade bearing on soil strengthened with aggregate piers. Finished piers may be up to 36 inches (900 mm) in diameter and 30 feet (9 m) deep.

the foundation be carried deeper. Underpinning methods generally rely on one of three approaches: The existing foundation elements may be enlarged to distribute loads over a greater soil area; new, deeper foundations can be inserted under existing ones to carry loads to a deeper, stronger stratum of soil; or the soil itself can be strengthened by grouting or chemical treatment. Figures 2.51 and 2.52 illustrate in diagrammatic form some selected concepts of underpinning.

Up–Down Construction

Normally, the substructure of a building is completed before work begins on its superstructure. If the building has several levels of basements, however, substructure work can take many months, or on very complex projects a year or more. In such a case, *up–down construction* may be an economical option, even if its first cost is somewhat more than that of the normal procedure, because it can save considerable construction time.

As diagrammed in Figure 2.53, up–down construction begins with installation of a perimeter slurry

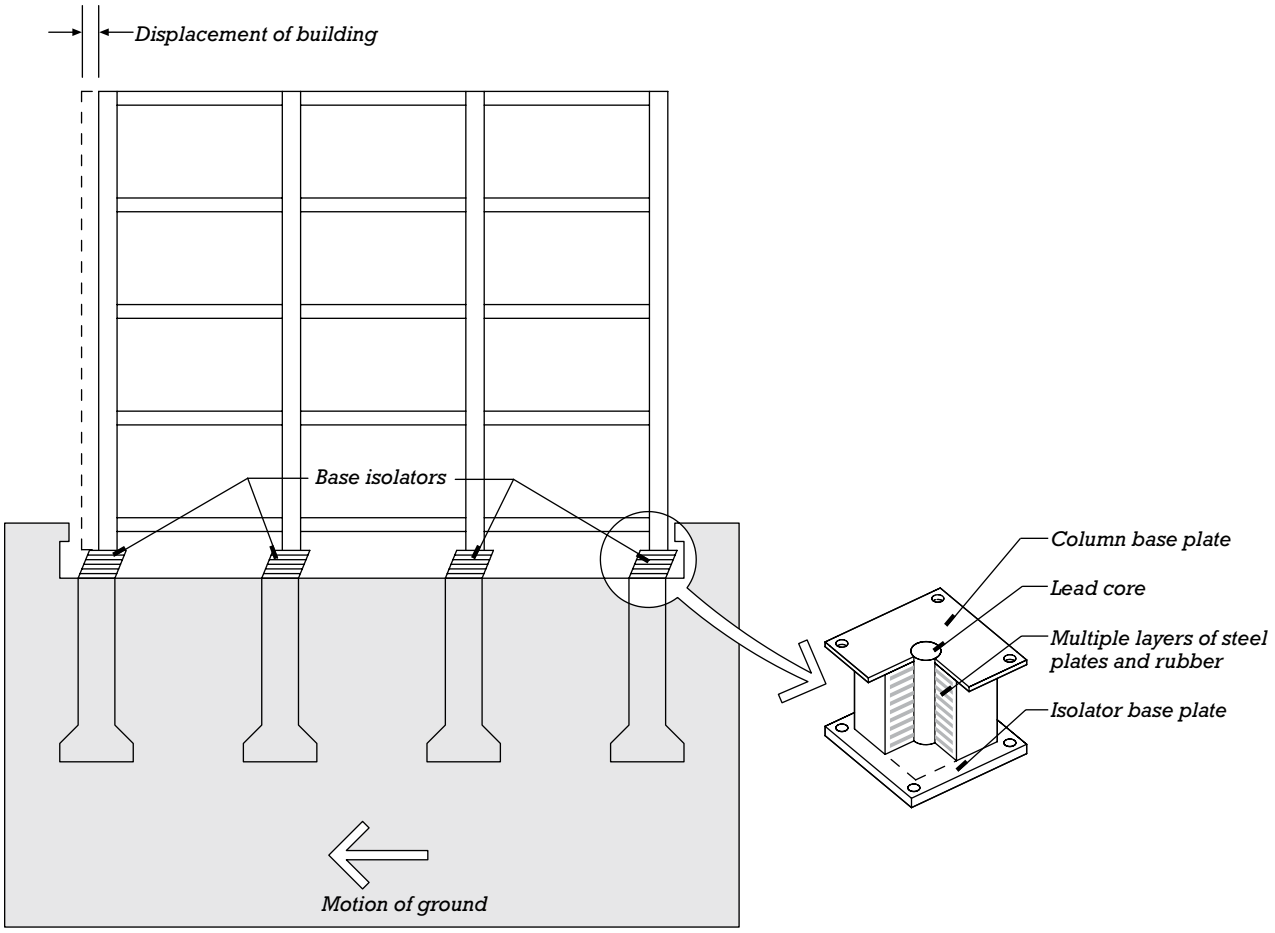


FIGURE 2.50
Base isolation.

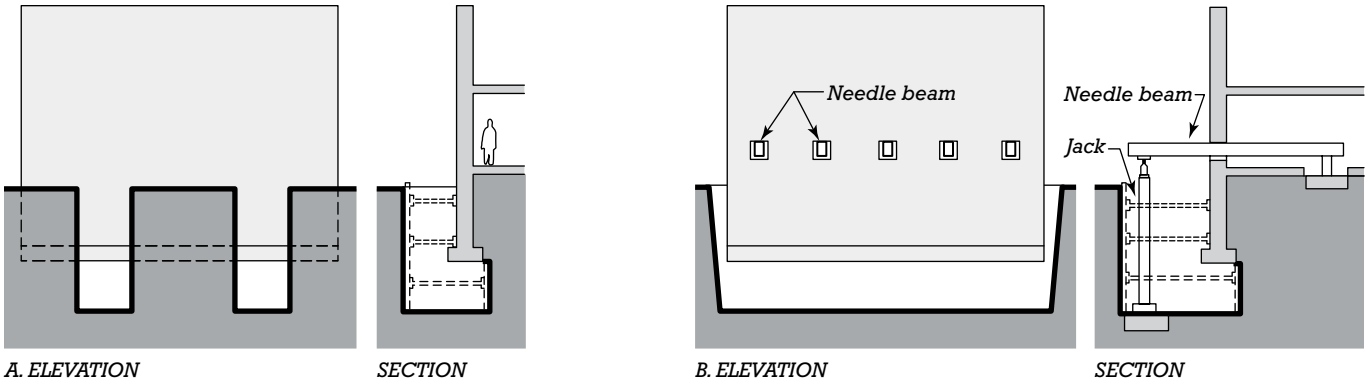


FIGURE 2.51
Two methods of supporting a building while carrying out underpinning work beneath its foundation, each shown in both elevation and section. (*A*) Trenches are dug beneath the existing foundation at intervals, leaving the majority of the foundation supported by the soil. When portions of the new foundations have been completed in the trenches, another set of trenches is dug between them and the remainder of the foundations is completed. (*B*) The foundation of an entire wall can be exposed at once by needling, in which the wall is supported temporarily on needle beams threaded through holes cut in the wall. After underpinning has been accomplished, the jacks and needle beams are removed and the trench is backfilled.

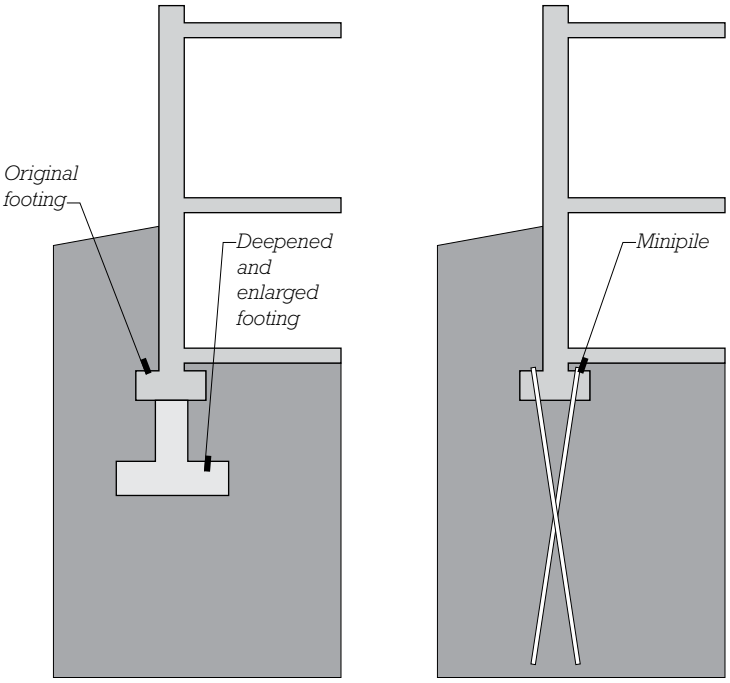


FIGURE 2.52
Two methods of foundation underpinning. (*Left*) After temporarily supporting the original footing using one of the methods illustrated in Figure 2.51, a new deeper and larger footing is constructed below. (*Right*) Rows of minipiles are driven through the existing footing and into the soil below. With this method, excavation is required only so deep as is needed to expose the top of the footing, and no temporary support of the foundation is required.

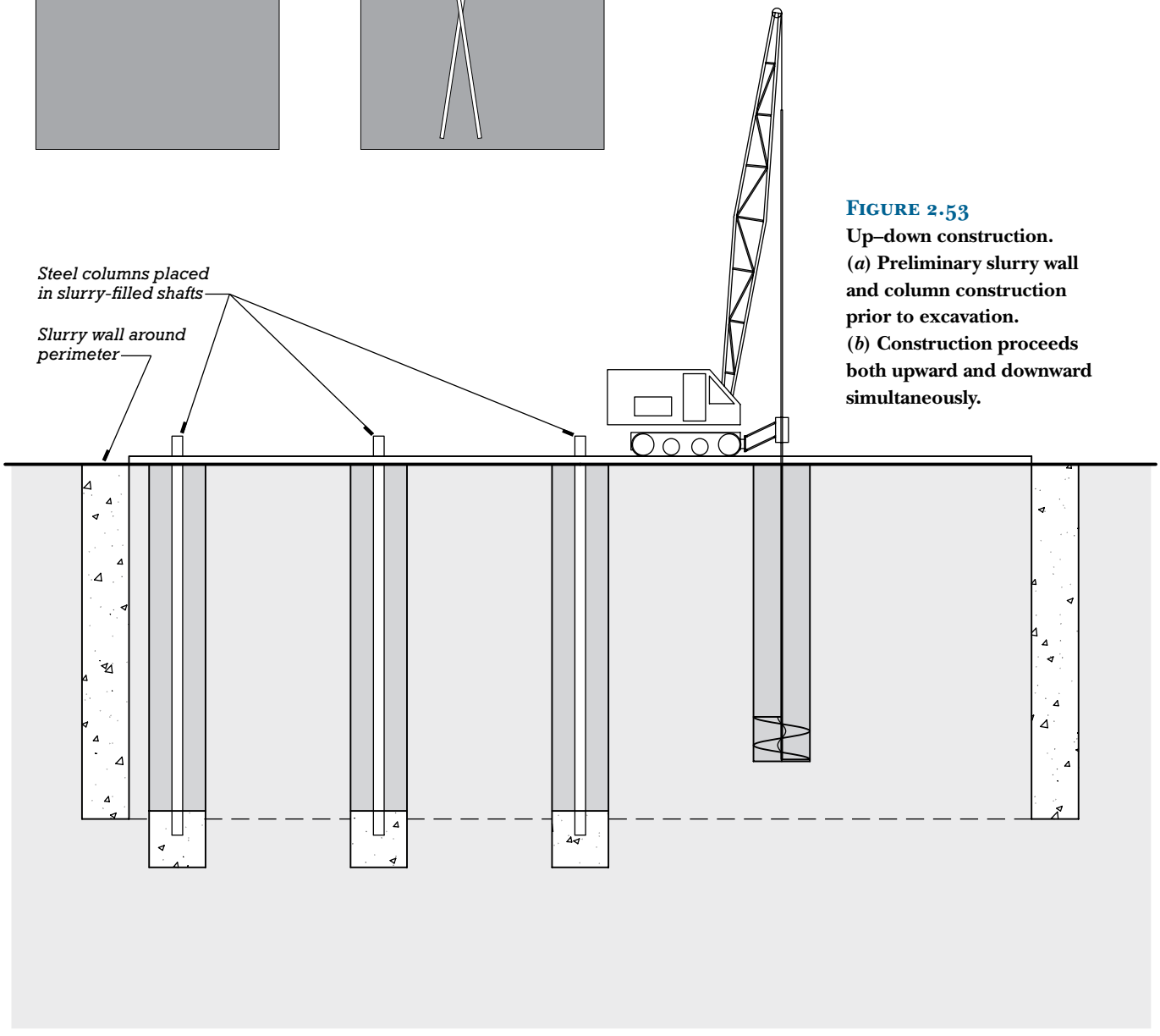


FIGURE 2.53
Up–down construction. (*a*) Preliminary slurry wall and column construction prior to excavation. (*b*) Construction proceeds both upward and downward simultaneously.

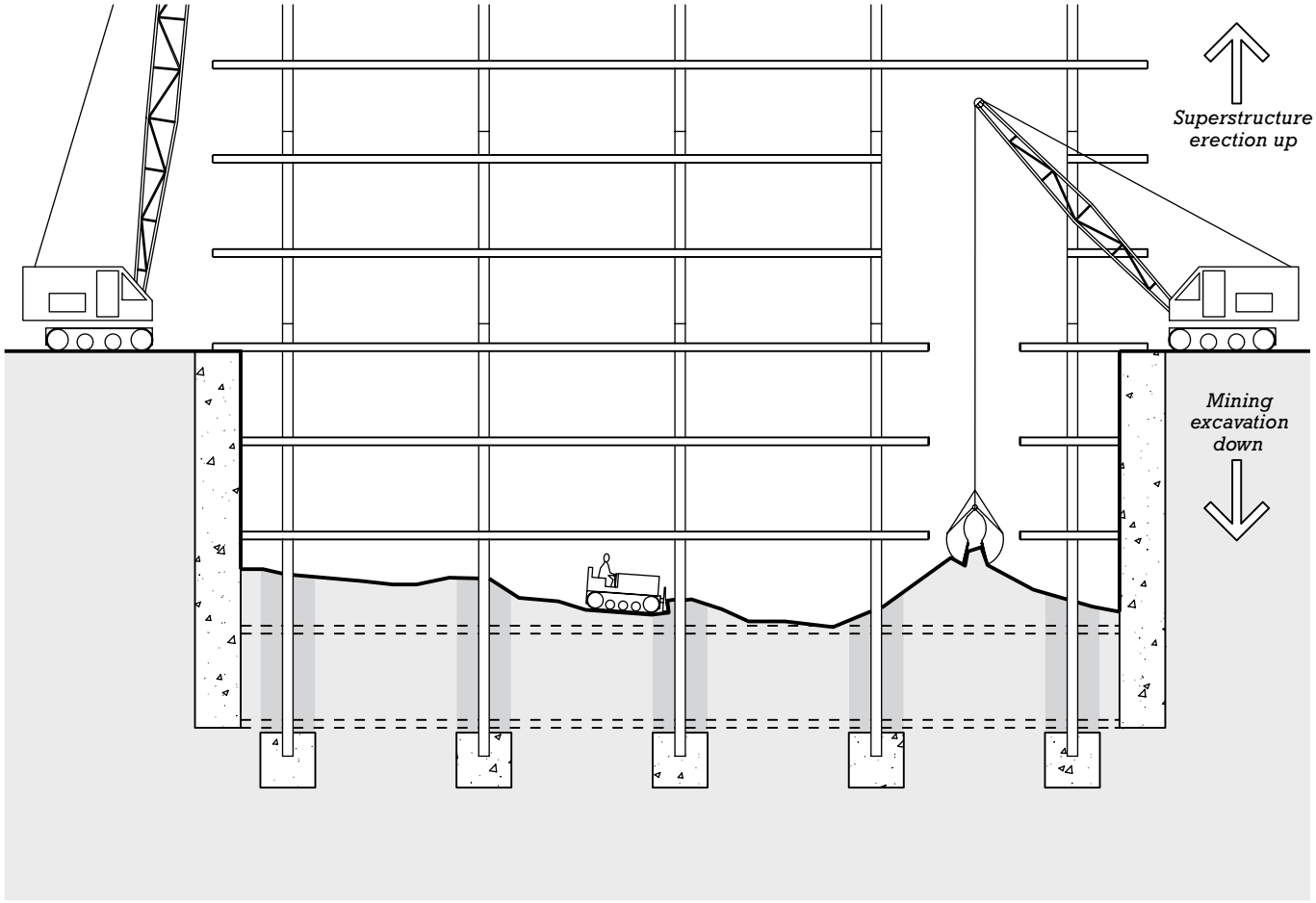
wall, tangent wall, or other method of foundation wall construction that precedes excavation. Internal steel columns for the substructure are lowered into drilled, slurry-filled holes, and concrete footings are tremied beneath them. After the ground-floor slab is in place and connected to the substructure columns, erection of the superstructure may begin. Construction continues simultaneously on the substructure, largely by means of relatively tedious mining techniques: A story of soil is excavated from beneath the ground-floor slab and a level "mud slab" of controlled low-strength material (see the "Filling and Finish Grading" section in this chapter) is poured. Working on the mud slab, workers reinforce and pour a concrete structural slab for the floor of the topmost basement level and connect this floor to the columns. When the slab is sufficiently strong, another story of soil is removed from beneath it, along with the mud slab. The process is repeated until the substructure is complete, by which time the superstructure has simultaneously been built many stories into the air.

Foundations as Building Enclosure

Waterproofing and Drainage

Where building substructures enclose basements, parking garages, or other usable space, groundwater must be kept out. Concrete alone is seldom adequate for this purpose. Moisture can migrate through its microscopic pores, or through pathways created by shrinkage cracks, form-tie holes (see Chapter 14), utility penetrations, or the joints that occur between separate pours. Two strategies are used to resist water entry: drainage and a water barrier consisting of dampproofing or waterproofing.

Drainage draws groundwater away from a foundation, reducing the volume and pressure of water acting on the foundation's walls and slabs. It typically consists of some combination of porous backfill material (such as a well-sorted gravel), drainage mat, and perforated drain piping (Figure 2.54). *Drainage mat* is a manufactured sheet product, usually about ½ inch (12 mm) thick,



(*b*)

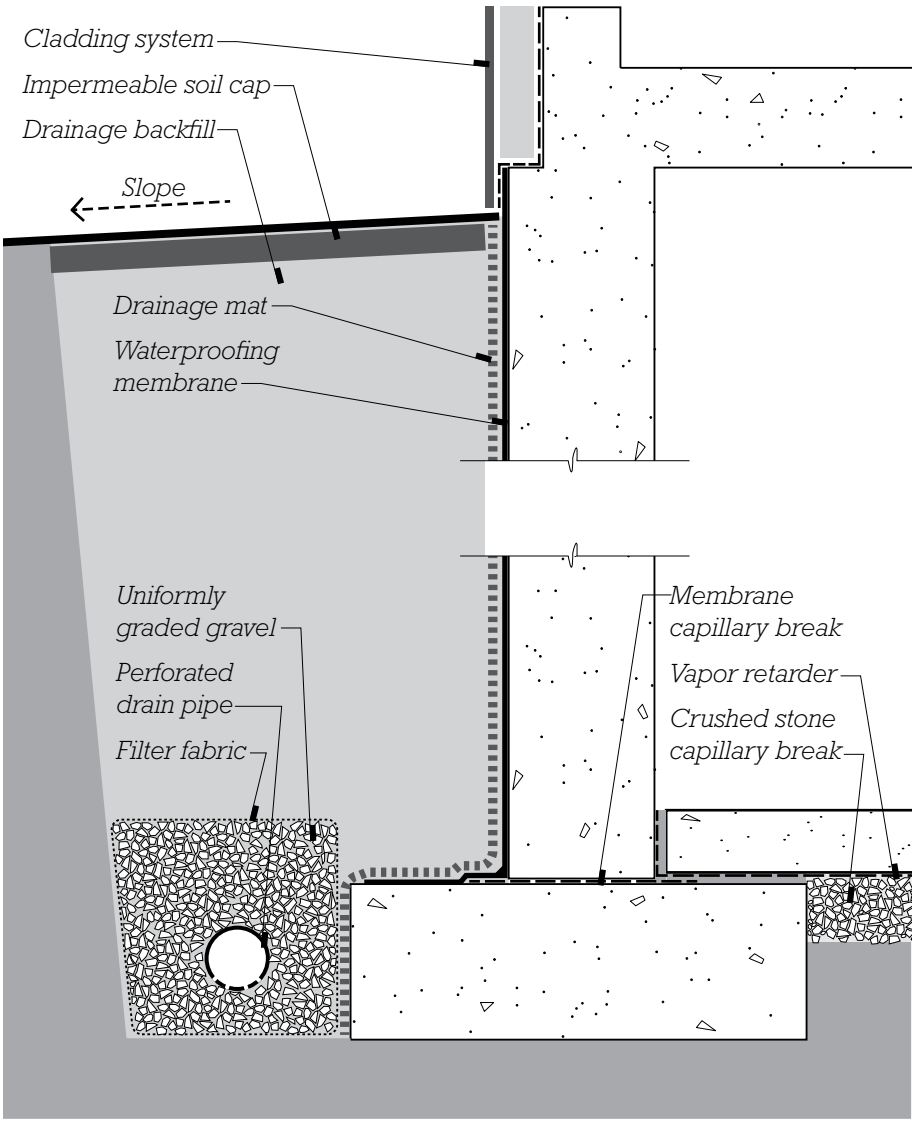


FIGURE 2.54
Typical foundation drainage and waterproofing. The ground surface slopes to direct surface water away from the foundation wall. Where flows are high, an impermeable clay soil cap may be added to further reduce water infiltration into the soil. The exterior face of the foundation wall is protected with a drainage mat and waterproofing membrane. Perforated drain pipe is set below the level of the interior slab. The pipe is surrounded with a highly drainable layer of uniformly graded gravel, and the gravel is wrapped with filter fabric to protect against siltation. A capillary break, such as a sheet or liquid-applied membrane, is installed on top of the footing to protect against "rising damp," that is, ground moisture diffusing up through the footing into the foundation wall above. The concrete slab on grade is also protected from ground moisture by a vapor retarder membrane and a capillary break of crushed stone below. In areas of high seismic activity, the benefits of a membrane between the footing and wall must be balanced with the engineering requirement for direct concrete-to-concrete contact between these two parts to provide added shear strength, or resistance to sliding, at this connection. Concrete reinforcing is omitted for clarity.

made of a plastic egg-crate-like structure or some other very open, porous material. It is faced on one side with *filter fabric* that allows water to pass easily but prevents fine soil particles from entering and clogging its passages. Subgrade water that approaches the foundation wall falls through the mat to *perforated drain piping* at the bottom of the wall. The drain piping is laid around the outside perimeter of the building foundation. The pipes are 4 or 6 inches (100 or 150 mm) in diameter, with several parallel rows of perforations that allow the inflow of water that arrives at that level. Water in the pipes then flows by gravity either to daylight at a lower surface elevation on a sloping site, a municipal storm sewer system, or a sump pit that can be automatically pumped dry whenever it fills. The perforations in the pipes face downward so that as the water level in the soil rises, it enters the pipes at the lowest possible level. Where groundwater conditions are severe, rows of perforated pipe may be installed under the basement slab as well.

On many substructures, a barrier of some kind is added to increase protection against water entry. *Dampproofing* is a moisture-resistant cement plaster or asphalt compound applied to basement walls where groundwater conditions are mild or waterproofing requirements are not critical. *Cement plaster dampproofing*, or *parge coating*, is light gray in color and is troweled on. *Asphalt* (*bituminous*) *dampproofing* is almost black in color and applied as a liquid by spray, roller, or trowel.

Compared to dampproofing, *waterproofing* provides more robust

protection against water entry. With careful design and installation, it can reliably protect interior spaces from moisture in very wet soils or even when foundations are submerged below the surrounding water table and exposed to continuous hydrostatic pressures.

Waterproofing membranes are formulated from plastics, asphalt compounds, synthetic rubbers, natural clays, and other materials applied in diverse forms. *Liquid-applied membranes* are sprayed or rolled on as viscous liquids that cure in place. They are seamless and easy to form around intricate shapes. *Sheet membranes* are manufactured in the factory (Figure 2.55). They are consistent in quality and thickness, but more difficult to apply around complex shapes and more vulnerable to leakage at the seams between sheets. *Fully adhered membranes* are continuously bonded to the substrate to which they are applied, limiting the chance for leaks to spread underneath the membrane. Other membranes are *loosely laid*, making them less vulnerable to tears or ruptures caused by movements in the substrate. *Pre-applied membranes* are installed before concrete is poured, which is useful for waterproofing beneath concrete slabs on grade or at blind-side wall conditions (see Figure 2.56). *Integral waterproofing*, added to the wet concrete mixture, plugs up small pores and microcracks in hardened concrete, making the concrete itself more watertight.

Joints in foundation construction, such as those occurring between

FIGURE 2.55
Waterproofing in progress on a concrete foundation. *Leftmost*: The bare foundation wall remains exposed. *Middle*: The waterproofing panels consist of an expansive, impermeable bentonite clay sandwiched within geotextile fabric layers and faced with a high-density polyethene sheet. *Right*: Drainage mat has been installed over the waterproofing. The mat's outer face of filter fabric is lightly dimpled, telegraphing the egg-crate structure of the underlying molded plastic panel. The top edge of the mat is secured in place with an aluminum *termination bar* that holds the mat in place and keeps dirt and debris from falling behind it. *Lower right*: White, plastic perforated drain piping can be seen, temporarily supported on wood blocking and running alongside the footing. *(Photo by Joseph Iano.)*

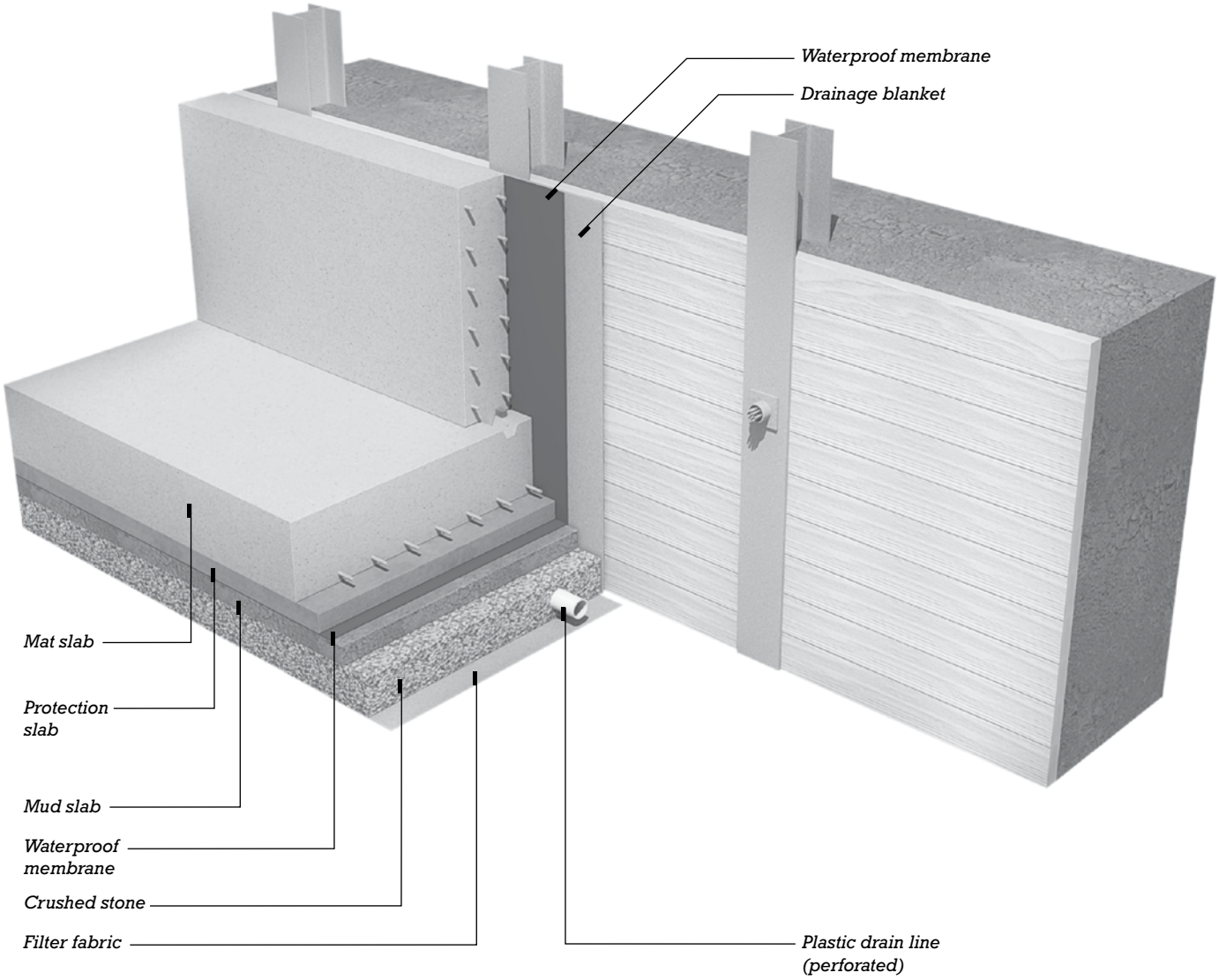


FIGURE 2.56

***Blind-side waterproofing* is used where there is no working space between a sheeted excavation and the outside of the foundation wall. This condition occurs most frequently when foundations are constructed directly along a property line. The drainage mat and a pre-applied waterproofing membrane are attached to the sheeting. Then the foundation wall is poured against them. In this illustration, the waterproofing extends under the foundation mat as well. Where groundwater conditions are severe, waterproofing under the basement slab or mat provides greater protection against water intrusion than a less expensive and easier to install vapor retarder membrane.**

separate concrete pours, require attention to ensure watertightness as well. Preformed *waterstops* made of plastic, synthetic rubber, metal, or materials that swell when they come in contact with water can be cast into the mating concrete edges to block the passage of water through these especially vulnerable locations (Figures 2.57, 2.58, and 2.59).

Below-grade waterproofing becomes difficult or impossible to access once construction is complete yet must perform trouble-free for the life of the building. To guard against future leaks, membranes are carefully inspected during installation. Various testing methods, such as *flood testing* of horizontal membranes (in which the membrane is submerged for a period of time and checked for leaks), may also be performed. Once inspection and testing are complete, membranes are covered with a *protection board*, insulation board, or drainage mat to shield the membrane from prolonged exposure to sunlight before they are covered and to prevent damage during soil backfilling.

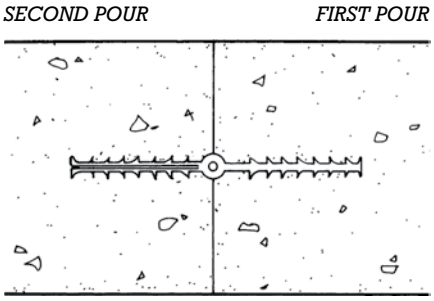


FIGURE 2.57
A synthetic rubber waterstop is used to seal against water penetration at joints in concrete construction. The type shown here is split on one side so that its halves can be placed flat against the formwork where another wall will join the one being poured. After the concrete has been poured and the formwork has been removed from the first wall, the split halves are folded back together before the next wall is poured. (This type of waterstop can be used for both movement and nonmovement joints in the wall.)

FIGURE 2.58
A synthetic rubber waterstop ready for the next pour of a concrete wall, as diagrammed in Figure 2.60. *(Courtesy of Vulcan Metal Products, Inc., Birmingham, Alabama.)*

FIGURE 2.59
A swelling bentonite waterstop is adhered to a concrete footing prior to casting of the concrete wall above. Later, if groundwater seeps into this area, the bentonite will swell to fully seal the joint. Because of bentonite's expansive force, the waterstop must not be positioned too close to the surface of the wall, or it could cause portions of concrete to split away when it swells. *(Photo by Joseph Iano.)*

Thermal Insulation

Occupant comfort and energy efficiency require that occupied basements be thermally insulated to limit their loss of heat to the surrounding soil. On the outside of the foundation wall, water-resistant insulation materials with good compressive strength, such as extruded polystyrene foam or mineral-fiber insulation boards, may be placed against the wall and held by adhesive, fasteners, or the pressure of the soil (Figure 2.60). On the inside of the wall, insulation may be attached directly to the wall and/or installed in a separately framed partition built close to the inside of the wall (Figure 5.8*B*). Insulation may also be integrated into the foundation wall itself, such as with insulated concrete forms (Figure 14.40).

Figure 2.61 shows two methods for insulating concrete slab on grade foundations. Typical insulation thicknesses range from 1 to 4 inches (25 to 100 mm). Insulation is normally only required for a specified portion of the slab perimeter rather than beneath the entire slab. Such *perimeter insulation* must protect the vertical edge of the slab and extend from 1 to 4 feet (300 to 1200 mm) either under the slab, straight downward, or outward from the slab edge. When slabs are heated, such as with embedded hydronic tubing, insulation is required under the entire slab. Or, when slabs are protected by insulated foundation walls, or sufficiently far below grade, no insulation is required.

Radon and Soil Gas Control

Radon is a cancer-causing gas that occurs naturally within soils and whose prevalence varies by region and locality. Where concentrations in the soil are high, gas seeping through cracks and unsealed penetrations in the foundation can accumulate to

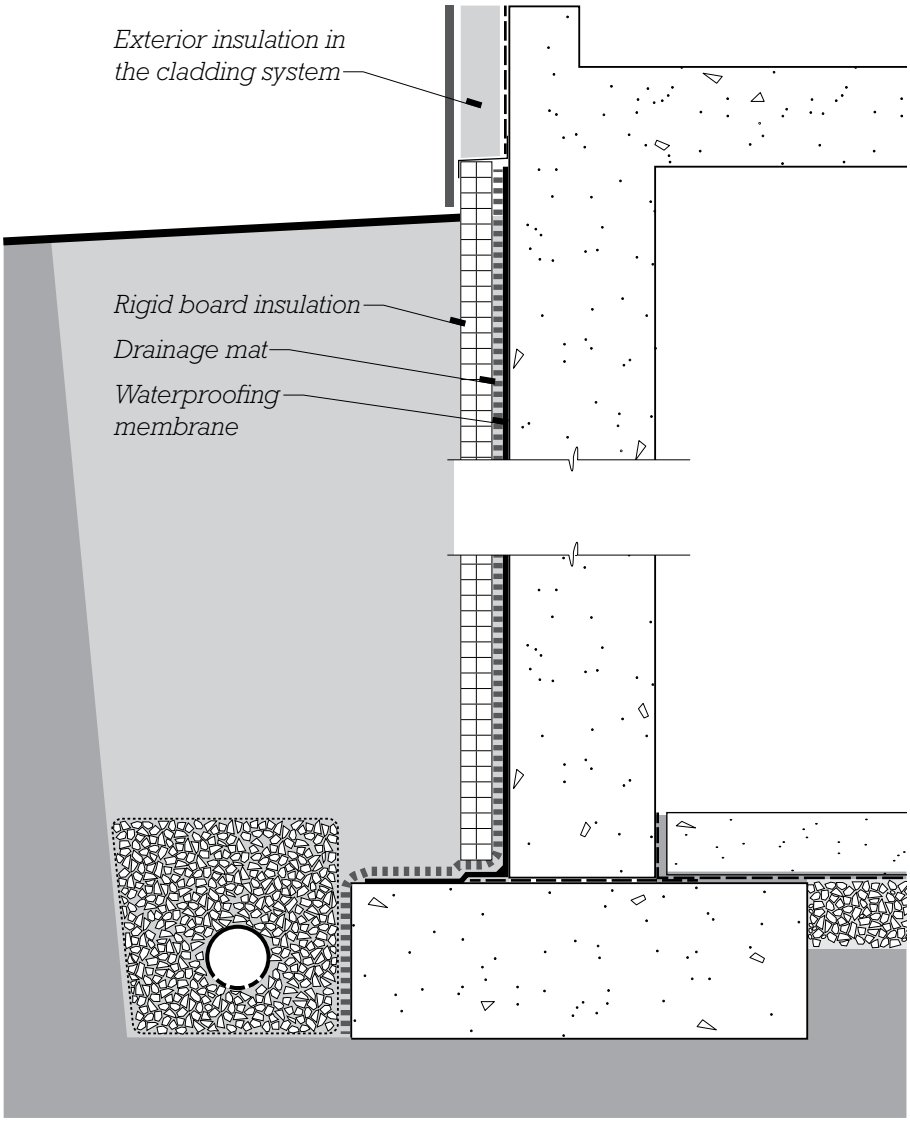


Figure 2.60
Exterior insulation added to a foundation similar to the one shown in Figure 2.54. Rigid board insulation, usually 1 to 4 inches (25 to 100 mm) thick, is easily added to the exterior side of the foundation wall. The insulation can be placed over the drainage mat as shown here, or it can be installed directly against the waterproofing with the drainage mat following afterward. When the above-grade cladding system includes exterior insulation, it is beneficial to energy performance to align these two insulation materials to form a continuous layer of thermal control.

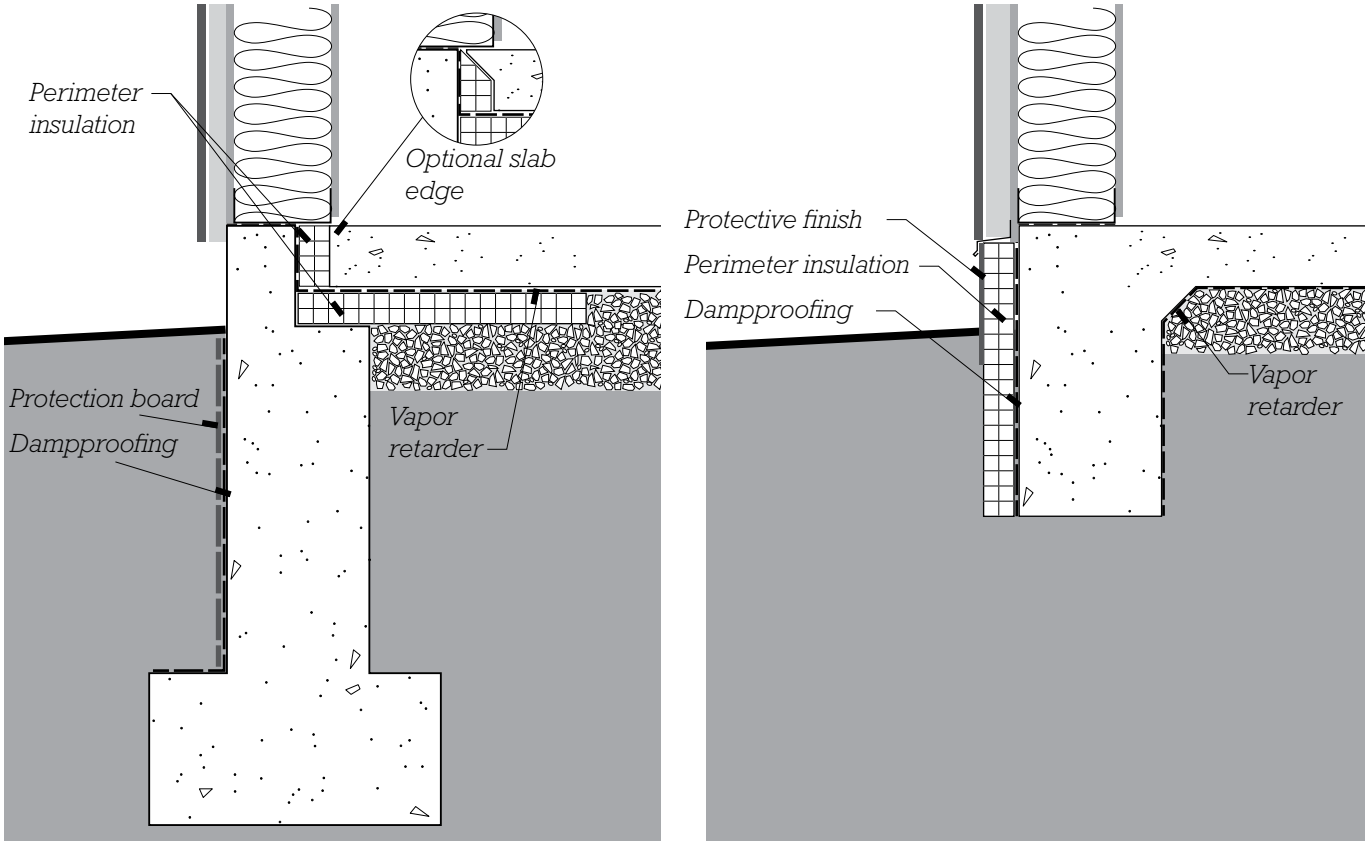


FIGURE 2.61

(*Left*) Perimeter insulation located inside of the foundation wall. The insulation protects the vertical slab edge and extends a specified distance under the slab. Where the wall framing above does not adequately conceal the insulation, the insulation may be beveled at a 45° angle as shown in the optional detail. The dampproofing and protection board shown are also optional, their use depending on the severity of groundwater and soil drainage conditions. (*Right*) Perimeter insulation located outside of the foundation wall. Where the insulation extends above grade, it is covered with a finish material that protects against sunlight and physical damage. Optionally, the underslab vapor retarder may extend under the footing to more completely protect the concrete from moisture in the ground. However, this may not be practical in areas of strong seismic activity, where the concrete footing must remain in direct contact with the earth. Where groundwater conditions are severe, drainage mat or drainage fill and perimeter footing drains can be added to either detail.

unhealthful levels within the building. In locations of known high risk for radon gas soil emissions, *passive radon control* is used to minimize gas infiltration into the building. For a typical basement with concrete slab on grade, this includes:

- A layer of gravel or other gas-permeable material beneath the concrete slab
- Over the gravel layer, a gas-impermeable plastic sheet or membrane
- After the pouring of the concrete foundation walls and slab on grade, sealing of all joints, penetrations, and cracks in these components
- Coating of the outside of basement walls with dampproofing or waterproofing
- One or more vent pipes extending vertically from the gas-permeable gravel layer through the roof of the building

This type of passive control is most frequently applied to residential and school buildings. Because many of the necessary components are normally included for the purposes of waterproofing and drainage, the added cost at the time of construction is small (Figure 2.62).

If, at some time after completion of the building, passive protection proves inadequate to control gas entry into the structure, *active sub-slab depressurization* can be added by installing small electric fans in the vertical vent pipes. These fans reduce the air pressure in the gas-permeable layer under the slab relative to the building interior, causing gasses to be more effectively extracted from this layer and exhausted to the exterior before they can infiltrate to the building interior.

Similar passive and active techniques may be used to protect building interiors from other potentially hazardous *soil gasses* or emissions originating from herbicides or pesticides introduced into soil around a structure,

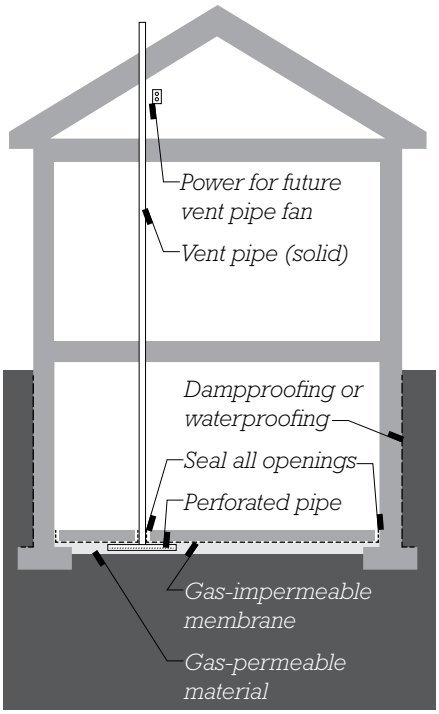


FIGURE 2.62
Passive radon protection. Many subslab vapor retarder membranes and suitably graded crushed-stone or gravel capillary breaks can perform as the gas-impermeable membrane and gas-permeable layer. The horizontal section of vent piping embedded in the gas-permeable layer is perforated, while the vertical riser, exposed to interior living space, is solid. Provision is also made for the installation of an electric fan, to allow for future active depressurization of the subslab space if needed.

fuel leakage from buried storage tanks, contaminated groundwater, covered landfills, or buried industrial pollution.

SITEWORK

Retaining Walls

A *retaining wall* holds back soil where an abrupt change in ground elevation occurs. The wall must resist the forces of the earth and groundwater that press against it from the uphill side. Retaining walls may be made of masonry, preservative-treated wood, coated steel, precast concrete, or, most commonly, sitecast concrete.

The design of a retaining wall must take into account the height of the wall, the pressures acting on the wall, and the character of the soil on which the wall will rest. If inadequately structured, failure can occur by overturning, sliding, or undermining (Figure 2.63).

For small retaining walls, unreinforced construction methods are used that rely on the mass of the wall, interlocking units, or other simple techniques to develop adequate resistance to soil pressures (Figures 2.64 and 2.65). For taller walls or ones subject to greater loads, more complex, reinforced solutions are required (Figure 2.66).

Gabions are another form of earth retention in which corrosion-resistant wire baskets are filled with cobble- or boulder-sized rocks and then stacked to form retaining walls and slope protection. Retaining walls of this type rely on the mass of the wall to resist the lateral earth pressures.

Earth Reinforcing

An alternative to structured earth retaining is *earth reinforcing*, or *mechanically stabilized earth*. Soil is compacted in layers, each sandwiched between reinforcing made of strips of galvanized steel or grids or mats of high-strength polymers called *geotextiles*. The reinforcing layers add tensile strength and stabilize the soil mass (Figure 2.67).

Layered geotextiles can also be used to strengthen engineered fill beneath shallow footings or to stabilize steep slopes or marginal soils under driveways, roads, or airport runways. Soil mixing, rock anchors, and soil nailing—all techniques discussed earlier in this chapter—can also be used to strengthen and stabilize underground soils, but without requiring excavation.

Filling and Finish Grading

Filling refers broadly to any placing of earth material (for example, to raise an existing grade), whereas *backfilling* refers more specifically to the replacement of soil materials in an excavation to restore it close to its finished level. Backfilling occurs around foundations and substructures, in utility trenches, and behind retaining walls.

For any type of filling, an appropriate type of replacement soil is added in layers, or *lifts*, which may range from 4 inches to roughly a foot (100 to 300 mm) in depth. Each lift is compacted before the next is added. Compaction may be performed by

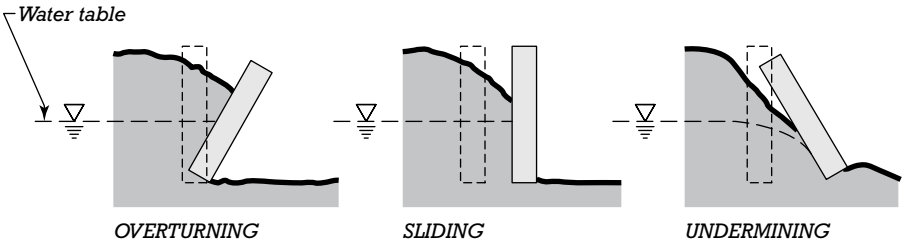
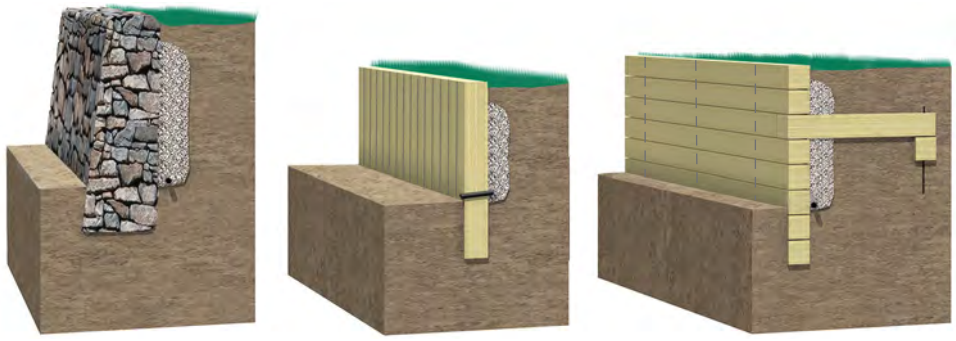


FIGURE 2.63
Three failure mechanisms in retaining walls. The high water table shown in these illustrations creates pressure against the walls that contributes to their failure. The undermining failure is directly attributable to groundwater running beneath the base of the wall, carrying soil with it.



STONE GRAVITY WALL *VERTICAL TIMBER CANTILEVERED WALL* *HORIZONTAL TIMBER WALL WITH DEADMEN*

FIGURE 2.64
Three types of simple retaining walls, usually used for heights not exceeding 3 feet (900 mm). The deadmen in the horizontal timber wall are timbers embedded in the soil behind the wall and connected to it with timbers inserted into the wall at right angles. The timbers, which should be pressure treated with a wood preservative, are held together with very large spikes or with steel reinforcing bars driven into drilled holes. The crushed-stone drainage trench behind each wall is important as a means of relieving water pressure against the wall to prevent wall failure. With proper engineering design, any of these types of construction can also be used for taller retaining walls.

FIGURE 2.65
A segmental retaining wall consisting of specially made concrete blocks designed to interlock and prevent sliding. The wall leans back against the soil it retains; this reduces the amount of soil the wall must retain and makes it more stable against the lateral push of the soil. *(Courtesy of VERSA-LOK Retaining Wall Systems.)*

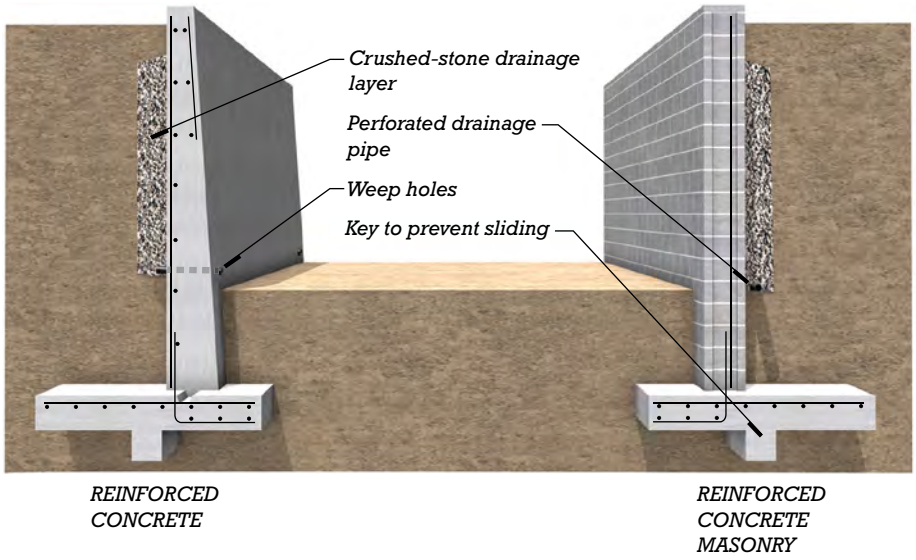


FIGURE 2.66
Cantilevered retaining walls of concrete and concrete masonry. The footing is shaped to resist sliding and overturning, and drainage behind the wall reduces the likelihood of undermining. The pattern of steel reinforcing (broken lines) is designed to resist the tensile forces in the wall.

FIGURE 2.67
A retaining wall made of precast concrete panels fastened to long galvanized steel straps that run back into the soil.

heavy rolling, vibrating, or ramming, depending on soil type and depth of lift. Small, walk-behind machines are used in confined areas, and larger machinery is used over larger areas.

To achieve optimal compaction and minimize future settlement, fill material must be moist enough to readily compress into a dense particle arrangement, but not so wet as to become unstable or soupy. Where backfill material will support slabs, pavements, or foundations, its strength and settlement properties are critical, and the soil materials, moisture content, and compaction work are all monitored by on-site engineers to ensure that the required performance will be achieved.

Around foundations, waterproofing, insulation, and drainage components must be in place before backfilling can begin. In addition, sufficient internal structure must be constructed to provide bracing for the foundation wall, so that the wall can resist the lateral loading from the backfilled soil. For example, in residential construction, the first-floor platform must be completed before foundation backfilling occurs, as this floor structure acts to laterally brace the top of the foundation wall (Figure 5.7).

Controlled low-strength material (*CLSM*) is a manufactured fill material made from portland cement and/or fly ash (a byproduct of coal-burning power plants), sand, and water. CLSM, sometimes called "flowable fill," is delivered in concrete mixer trucks and poured into the excavation, where it compacts and levels itself, then hardens. CLSM may be used to replace pockets of unstable soil encountered beneath a substructure or to backfill around basement walls. The strength of CLSM is matched to the situation. For example, for a utility trench, CLSM is formulated so that it is weak enough to be excavated easily by ordinary digging equipment when the pipe requires servicing, yet is as strong as a normal, good-quality compacted backfill.

Finish grading refers to the final leveling and smoothing of soil surfaces to their required contours and elevations. Where plant materials are planned, finish grading includes the application of nutrient-rich, organic topsoil to depths suitable for supporting the growth of the types of

grass, plants, shrubs, or trees that have been specified by the landscape architect.

Designing Foundations

In foundation design, there are thresholds that, when crossed, cause significant, sudden increases in construction costs:

- *Building below the water table.* If the substructure and foundations of a building are above the water table, minimal effort will be required to keep the excavation dry during construction. Once the water table is reached, more expensive efforts will be needed to dewater the site, strengthen excavation support systems, waterproof the foundation, and protect the finished foundation against permanent hydrostatic pressures.
- *Building close to an existing structure.* If the excavation can be kept well away from adjacent structures, the foundations of these structures will remain undisturbed and no effort or special expense will be required to protect them. When digging close to an existing structure, and especially when digging deeper than that structure's foundations, temporary bracing or permanent underpinning may be required to prevent disturbance.
- *Increasing the column or wall load from a building beyond what can be supported by a shallow foundation.* Shallow foundations are far less expensive than piles or caissons under most conditions. If the building grows too high, or is structured so that individual column loads are too high, a shallow foundation may no longer be able to carry the load and a more expensive, deep foundation system may be required.

For one- and two-family dwellings, foundation design is usually much simpler than for larger buildings. Foundation loadings are low and the uncertainties in design can be reduced by adopting a large factor of safety in calculating the bearing capacity of the soil. Unless the designer has reason to suspect poor soil conditions, the footings are designed using rule-of-thumb allowable soil stresses and standardized footing dimensions. The designer then examines the actual soil when the excavations have been made. If it is not of the quality that was expected, the footings may be redesigned using a revised estimate of soil-bearing capacity. If unexpected groundwater is encountered, better drainage may have to be provided around the foundation. In contrast, as discussed throughout this chapter, foundation design for larger buildings requires investigation and analysis of existing soils conditions, engineering design of the foundation components, and site supervision during construction.

Foundations and the Building Code

Because of the public safety considerations involved, building codes contain numerous provisions relating to the design and construction of excavations and foundations. The International Building Code defines which soil types are considered satisfactory for bearing the weight of buildings and establishes a set of requirements for subsurface exploration, soil testing, and submission of soil reports to the local building inspector. It goes on to specify the methods of engineering design that may be used for the foundations. It sets forth maximum loadbearing values for soils that may be assumed in the absence of detailed test procedures (refer back to Figure 2.6). It establishes minimum dimensions for footings, caissons, piles, and foundation walls and contains lengthy discussions relating to the installation of piles and caissons and the drainage and waterproofing of substructures. This code also requires engineering design of retaining walls. In all, building codes attempt to ensure that every building will rest upon secure foundations and a dry substructure.

MasterFormat Sections for Foundations and Sitework

02 30 00	**SUBSURFACE INVESTIGATIONS**
07 10 00	**DAMPPROOFING AND WATERPROOFING**
07 11 00	Dampproofing
07 13 00	Sheet Waterproofing
07 14 00	Fluid-Applied Waterproofing
31 10 00	**SITE CLEARING**
31 20 00	**EARTH MOVING**
31 21 13	Radon Mitigation
31 22 00	Grading
31 23 00	Excavation and Fill
31 23 19	Dewatering
31 34 00	**SOIL REINFORCEMENT**
31 40 00	**SHORING AND UNDERPINNING**
31 50 00	**EXCAVATION SUPPORT AND PROTECTION**
31 60 00	**SPECIAL FOUNDATIONS AND LOAD-BEARING ELEMENTS**
31 62 00	Driven Piles
31 64 00	Caissons
31 66 13.13	Rammed Aggregate Piers
31 66 15	Helical Foundation Piles
32 30 00	**SITE IMPROVEMENTS**
32 32 00	Retaining Walls

Key Terms

foundation
dead load
live load
rain load
snow load
wind load
seismic load
lateral soil pressure load
buoyant uplift
flood load
horizontal thrust
settlement
uniform settlement
differential settlement
earth material
consolidated rock
bedrock
soil
boulder
cobble
gravel
sand
coarse-grained soil
silt
clay
fine-grained soil
organic soil
shear strength
frictional soil, cohesionless soil
soil pore
soil liquefaction
soil fabric
cohesive soil
plastic soil
liquid limit
expansive soil
soil gradation
well graded soil
poorly graded soil
uniformly graded soil
gap graded soil
poorly sorted soil
well sorted soil
allowable foundation pressure
allowable soil pressure
soil consolidation
imported soil
native soil
general-purpose fill
drainage fill
test pit
groundwater
water table
test boring
penetration sampler
soil load test
sieve
plastic limit
geotechnical report
brownfield site
earthwork
grubbing and clearing
excavation
benched excavation
maximum allowable slope, angle of repose
excavation support
shoring
H-pile
soldier beam
lagging
sheet piling, sheeting
pneumatically applied concrete, shotcrete
soil mixing
ground improvement, earth improvement
slurry wall
clamshell bucket
slurry
tremie
contiguous pier
tangent wall
secant wall
crosslot bracing
waler
raker
tieback
rock anchor
soil nailing
dewatering
sump
well point
watertight barrier wall, cutoff wall
soil freezing
superstructure
substructure
shallow foundation
deep foundation
spread footing
column footing
wall footing, strip footing
engineered fill
frost line
ice lens
slab on grade
crawlspace
basement
tie beam
combined footing
cantilever footing
shallow frost-protected foundation
mat foundation, raft foundation
floating foundation, compensated foundation
caisson, drilled pier
socketed caisson
belling
auger drill
belling bucket
belled caissonpile
end bearing pile
friction pile
pile cap
driven to refusal
grade beam
pile hammer
piledriver
timber pile
heaving
pipe pile
minipile, pin pile, micropile
helical pile, screw pile
precast concrete pile
sitecast concrete pile
pressure-injected footing, compaction grouted footing
rammed aggregate pier, stone column
base isolator
underpinning
up–down construction
drainage
drainage mat
filter fabric
perforated drain piping
dampproofing
cement plaster dampproofing, parge coating
asphalt dampproofing, bituminous dampproofing
waterproofing
liquid-applied membrane waterproofing
sheet membrane waterproofing
fully adhered membrane waterproofing
loosely laid membrane waterproofing
pre-applied membrane waterproofing
integral waterproofing
termination bar
blind-side waterproofing
waterstop
flood test
protection board
perimeter insulation
radon gas
passive radon control
active subslab depressurization
soil gas
retaining wall
gabion
earth reinforcing
mechanically stabilized earth
geotextile
filling
backfilling
soil lift
controlled low-strength material (CLSM)
finish grading

Review Questions

1. What is the nature of the most common type of foundation failure? What are its causes?

2. Explain the differences among sand, silt, and clay, both in their physical characteristics and their behavior in relation to building foundations.

3. Explain the difference between well graded and poorly graded soil. How does their behavior differ?

4. What is excavation sheeting used for? List three different types of excavation sheeting.

5. Under what conditions would you use a watertight barrier instead of well points when digging below the water table?

6. In cold climates, how does the frost line affect the placement of shallow footings? What footing type is an exception to this general principle?

7. If shallow foundations are substantially less costly than deep foundations, why do we use deep foundations?

8. What soil conditions favor piles over caissons? What type of pile is especially well suited to the repair or improvement of existing foundations and why?

9. List and explain some cost thresholds frequently encountered in foundation design.

10. Explain the difference between waterproofing and dampproofing. When is one or the other an appropriate choice for protecting a foundation from moisture?

11. List two types of waterproofing and describe one possible advantage of each.

12. List the components of a typical foundation drainage system and their functions.

Exercises

1. Obtain the foundation drawings and soils report for a nearby building. Look first at the log of test borings. What sorts of soils were found beneath the site? How deep is the water table? What types of foundations do you think might be suitable for use in this situation? Now look at the foundation drawings. What type was actually used? Can you explain why?

2. What types of foundation and substructure are normally used for houses in your area? Why?

3. Look at several excavations for major buildings under construction. Note carefully the arrangements made for excavation support and dewatering. How is the soil being loosened and carried away? What is being done with the excavated soil? What type of foundation is being installed? What provisions are being made to keep the substructure permanently dry?

Selected References

Cheng, Liu, and Jack Evett. *Soils and Foundations* (8th ed.). Boston, Pearson Education, 2014.

Provides detailed discussion of the engineering properties of soils, subsurface exploration techniques, soil mechanics, and shallow and deep foundations.

Kubal, Michael. *Construction Waterproofing Handbook* (2nd ed). New York, McGraw-Hill, 2008.

Covers all aspects of building waterproofing, both above and below grade.

National Roofing Contractors Association. *NRCA Waterproofing Manual.* Rosemont, IL, updated regularly.

Provides industry-standard guidelines and details for the application of waterproofing and dampproofing to building substructures.

Websites

CETCO Building Materials Group: www.cetco.com/en-us/Products/Building-Materials/Waterproofing

GCP Applied Technologies: gcpat.com/en/solutions/waterproofing-solutions-construction-projects

Geopier Foundation: www.geopier.com

Hayward Baker Geotechnical Construction: www.haywardbaker.com

Nicholson Construction Company: www.nicholsonconstruction.com/solutions

Schnabel Foundation Company: www.schnabel.com

Whole Building Design Guide, Foundation Walls: www.wbdg.org/guides-specifications/building-envelope-design-guide/below-grade-systems/foundation-walls

3

Wood

- **Trees**
  - Tree Growth
  - Softwoods and Hardwoods
  - Environmentally Certified Wood
  - Wood and Carbon

  Sustainability and Wood

- **Lumber**
  - Sawing
  - Seasoning
  - Surfacing
  - Lumber Defects
  - Lumber Grading
  - Structural Properties of Lumber
  - Lumber Dimensions
  - Veneer
- **Wood Products**
  - Glue-Laminated Wood
  - Cross-Laminated Timber
  - Nail-Laminated and Dowel-Laminated Timber
  - Structural Composite Lumber
  - Wood I-Joists
  - Other Wood Products
- **Plastic Lumber**
- **Wood Panel Products**
  - Structural Panel Types
  - Plywood Production
  - Specifying Structural Panels
  - Other Panel Products
- **Protecting Wood from Decay and Fire**
  - Biological Threats to Wood
  - Preservative-Treated Wood

  Chemical Wood Preservative Treatments

  - Other Treatments
  - Naturally Durable Woods
  - Fire-Retardant Treatments
- **Wood Fasteners and Adhesives**
  - Nails
  - Screws
  - Bolts
  - Timber Connectors
  - Toothed Plates
  - Metal Framing Devices
  - Wood Adhesives

  Wood Product Adhesives and Formaldehyde

- **Prefabricated Wood Components**
  - Trusses
  - Prefabricated Panels
  - Factory-Built Housing

Case Study: French American School

The Douglas fir tree, indigenous to the western United States and Canada, can grow as tall as roughly 300 feet (100 m). Its wood is prized for its strength, durability, and evenness of grain. *(Photo by Joseph Iano.)*

Wood is perhaps the most broadly loved of all the materials that we use for building. It delights the eye with its endlessly varied colors and grain patterns. It invites the hand to feel its subtle warmth and varied textures. When it is fresh from the saw, its fragrance enchants. We treasure its natural, organic qualities and take pleasure in its genuineness. Even as it ages, bleached by the sun, eroded by rain, worn by the passage of feet and the rubbing of hands, we find beauty in its transformations of color and texture.

Wood earns our respect as well as our love. It is strong and stiff, yet by far the least dense of the materials used for the beams and columns of buildings. It is worked and fastened easily with small, simple, relatively inexpensive tools. It is readily recycled from demolished buildings for use in new ones, and when finally discarded, it biodegrades rapidly to become natural soil. It is our only naturally renewable structural building material—one that will be available to us for as long as we manage our forests with an eye to the perpetual production of wood.

But wood, like a valued friend, has its idiosyncrasies. A piece of lumber is never perfectly straight or true, and its size and shape can change significantly with changes in the weather. Wood is peppered with defects that are relics of its growth and processing. Wood can split, warp, and give splinters. If ignited, wood burns. If left in a damp location, it decays and harbors destructive insects. The skillful designer and the seasoned carpenter, however, know all these things and understand how to build with wood to bring out its best qualities while neutralizing or minimizing its problems.

Trees

Wood comes from trees and is produced through natural growth processes. Understanding tree physiology is essential to knowing how to build with wood.

Tree Growth

The trunk of a tree is covered with a protective layer of dead *bark* (Figure 3.1). Inside the dead bark is a layer of living bark composed of hollow longitudinal cells that conduct nutrients downward from the leaves to the roots and other living parts of the tree. Inside this layer of living bark lies a very thin layer, the *cambium*, which creates new bark cells toward the outside of the trunk and new wood cells toward the inside. The thick layer of living wood cells inside the cambium is the *sapwood*. In this zone of the tree, nutrients are stored and sap is pumped upward from the roots to the leaves and distributed laterally in the trunk. At the inner edge of this zone, sapwood dies progressively and becomes *heartwood*. In many species of trees, heartwood is easily distinguished from sapwood by its darker color. Heartwood no longer participates in the life processes of the tree but continues to contribute to its structural strength. At the very center of the trunk, surrounded by heartwood, is the *pith* of the tree, a small zone of weak wood cells that were the first year's growth.

An examination of a small section of wood under a low-powered microscope shows that it consists primarily of tubular cells whose long axes are parallel to the long axis of the trunk. The cells are structured of tough *cellulose* and are bound together by a softer cementing substance called *lignin*. The direction of the long axes of the cells is referred to as the *grain* of the wood. Grain direction is important to the designer of wooden buildings because the appearance and physical properties of wood parallel to grain and perpendicular to grain are very different.

In temperate climates, the cambium begins to manufacture new sapwood cells in the spring, when the air is cool and groundwater is plentiful, conditions that favor rapid growth. Growth is slower during the heat of the summer, when water is scarce. *Springwood* (or *earlywood*) cells are therefore larger and less dense in substance than *summerwood* (or *latewood*) cells. Concentric bands of springwood and summerwood make up the annual growth rings in a trunk that can be counted to determine the age of a tree. The relative proportions of springwood and summerwood have a direct bearing on the structural properties of the wood a given tree will yield, because summerwood is stronger and stiffer than springwood. A tree grown under continuously moist, cool conditions grows faster than another tree of the same species grown under warmer, drier conditions, but its wood is not as dense or as strong.

Softwoods and Hardwoods

Softwoods come from coniferous trees and *hardwoods* from broadleafed trees. Most softwoods are cone-bearing, with needlelike leaves that remain on the trees during the colder winter

months. Most hardwoods drop their leaves seasonally. Also, as the names imply, softwoods are usually less dense and softer than hardwoods. But there are exceptions. The softwoods Douglas fir and longleaf pine, for example, are at least as dense as some hardwoods.

Nevertheless, the distinction between these two types of woods remains useful. Softwood trees have a relatively simple microstructure, consisting mainly of large longitudinal cells (*tracheids*) together with a small percentage of radial cells (*rays*). The tracheids provide long-distance transport of sap within the tree and account for most of the tree's structural strength. Rays provide for the storage and radial transfer of nutrients (Figure 3.2). Hardwood trees are more complex in structure, with a larger percentage of rays and two different types of longitudinal cells: small-diameter *fibers* and large-diameter *vessels*, or *pores* (Figure 3.3).

When cut into lumber, softwoods generally have a relatively coarse and plain grain structure, or *grain figure*, whereas many hardwoods show finer, more attractive patterns (Figure 3.4). Most of the lumber used today for the building structural frame comes from softwoods, which are comparatively plentiful and inexpensive. For furniture, cabinetry, interior paneling, flooring, and other fine woodwork, hardwoods (and some of the denser softwoods) are often chosen for their better stability, attractiveness, finishability, and resistance to wear. Examples of softwood and hardwood species used in North America, along with their principal uses, are listed in Figure 3.5. However, it should be borne in mind that thousands of species of wood are used in construction around the world and that available species vary considerably with geographic location. In North America, the major lumber-producing forests are in the western and eastern mountains of both the United States and Canada. Other regions, chiefly in the southeastern United States, also produce significant quantities.

FIGURE 3.1
Summerwood rings are prominent and a few rays are faintly visible in this cross section of an evergreen tree. But the cambium, which lies just beneath the thick layer of bark, is too thin to be seen, and heartwood cannot be distinguished visually from sapwood in this species.
(Courtesy of Forest Products Laboratory, Forest Service, USDA.)

Interactive Exercise

Environmentally Certified Wood

Environmentally certified wood comes from forests that are managed according to the guidelines of one of several organizations that set standards for long-term ecological sustainability, resource conservation, and other considerations. The *Forest Stewardship Council* (*FSC*) certification program encompasses ecological, economic, and social principles. It ensures responsible forest management practices that prevent overharvesting, maintain biological diversity, conserve natural resources, and protect the environment. It encourages efficient, economically sound use of forest products and services. Importantly, it also addresses respect for governing laws and international treaties, long-term tenure and land ownership rights and responsibilities, rights of indigenous peoples, community relations, and worker rights.

The Forest Stewardship Council establishes certification criteria and accredits other independent bodies that implement the certification process. FSC Forest Management Certification is applied to the forests where trees are harvested, and Chain of Custody Certification is applied to the manufacturers and distributors that process the wood after it leaves the forest, before it reaches the retailer or consumer. Specifying wood with Chain of Custody

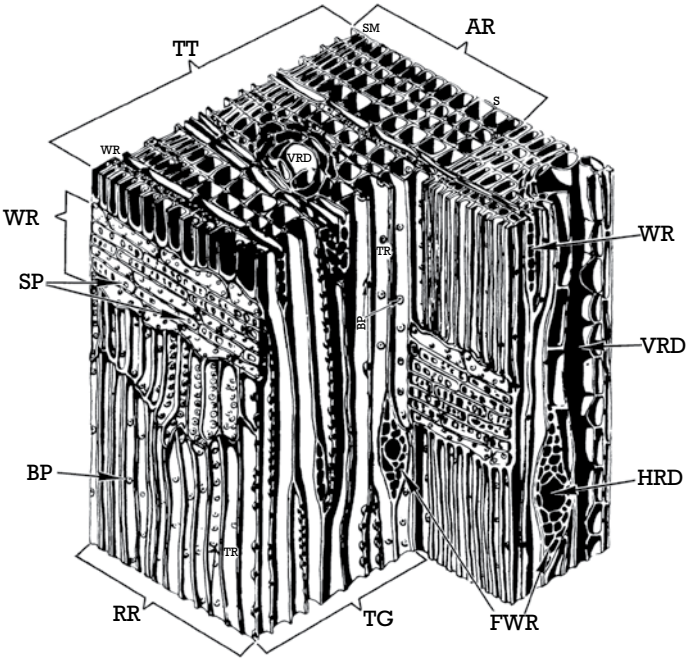


FIGURE 3.2

Cell structure of a softwood. Vertical cells (tracheids, labeled TR) dominate the structure of a softwood, seen here greatly enlarged. But rays (WR), which are cells that run radially from the center of the tree to the outside, are also in evidence. An annual ring (labeled AR) consists of a layer of smaller summerwood cells (SM) and layer of larger springwood cells (S). Simple pits (SP) allow sap to pass from ray cells to longitudinal cells and vice versa. Resin is stored in vertical and horizontal resin ducts (VRD and HRD), with the horizontal ducts centered in fusiform wood rays (FWR). Border pits (BP) allow for the transfer of sap between longitudinal cells. The face of the sample labeled RR represents a radial cut through the tree, and TG represents a tangential cut. *(Courtesy of Forest Products Laboratory, Forest Service, USDA.)*

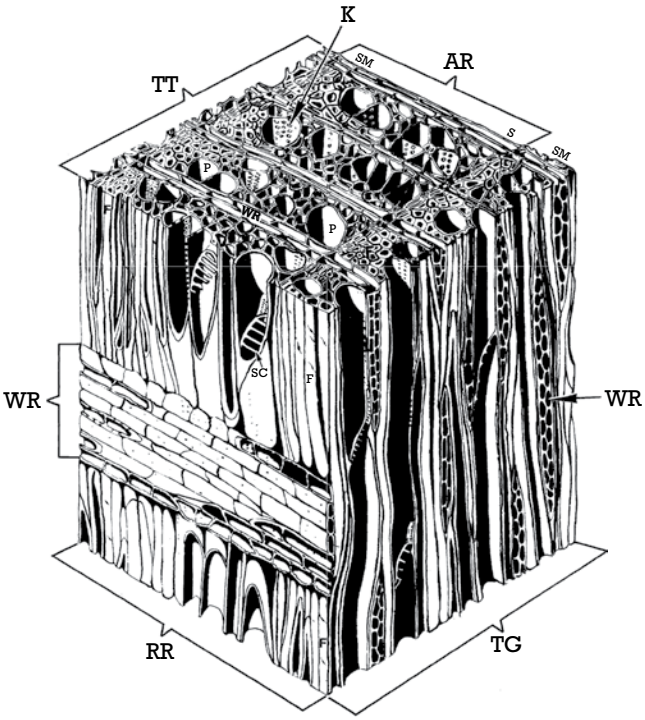


FIGURE 3.3

Cell structure of a hardwood. Rays (WR) constitute a large percentage of the mass of a hardwood and are sometimes strongly expressed in the grain figure. The vertical cell structure is more complex than that of a softwood, with large pores (P) to transport the sap and smaller wood fibers (F) to add strength to the wood. Pore cells in some hardwood species end with crossbars (SC), while those of other species are entirely open. Pits (K) pass sap from one cavity to another. *(Courtesy of Forest Products Laboratory, Forest Service, USDA.)*

Certification ensures that the wood arriving on the construction site originated from a certified forest and was harvested and processed according to FSC criteria.

Other certification systems with a significant presence in the North American lumber market include the Sustainable Forestry Initiative, the American Tree Farm System, the Canadian Standards Association Sustainable Forests Management System, and the Programme for the Endorsement of Forest Certification.

Wood and Carbon

Wood is unique among major structural materials in its participation in the Earth's natural carbon cycles. Around the globe, tens of billions of tons of *sequestered carbon* are stored in the trees, ground litter, and soil of forests. Each year, hundreds of millions of tons of carbon are captured by new forest growth, while at the same time, deforestation, especially in tropical areas, is a significant source of carbon dioxide emissions.

Carbon accounts for roughly half the weight of dry wood. And when lumber is extracted from the forest and placed into use in buildings, this carbon remains stored within it. For example, the U.S. housing stock is estimated to account for between 600 million and 1 billion (500 million and 1 billion metric) tons of sequestered carbon. Acting this way, as a large carbon sink, wood construction helps to mitigate global warming.

However, assessing the global warming impact of sequestered carbon in wood building products also has unique complexities. For example, the value of carbon sequestration should only be counted when the forest of origin is managed sustainably, such that new trees are planted to replace those taken for use in wood products manufacture. Additionally, if carbon content is to be counted, the eventual release of this carbon back into the atmosphere at the product's end of life, when it decays, is buried in a landfill, or is incinerated, should also be considered. For this reason, the impact of

sequestered carbon is omitted from cradle-to-gate life-cycle analyses, which do not incorporate material end-of-life effects. But the beneficial impact of sequestered carbon may be part of a cradle-to-grave analysis, which can also account for the potential return of carbon to the atmosphere under various material reuse or disposal scenarios. The length of time horizon chosen for a cradle-to-grave analysis in relation to forest harvesting and regeneration cycles, assumptions about the decay rates and decay products of lumber buried in anaerobic (oxygen deprived) landfills, and other factors can further complicate such analyses.

At this time, the science used to account for the role of sequestered carbon in wood products is not fully settled, and readers should expect to encounter significant ranges in assessed impacts, depending on the methodologies employed.

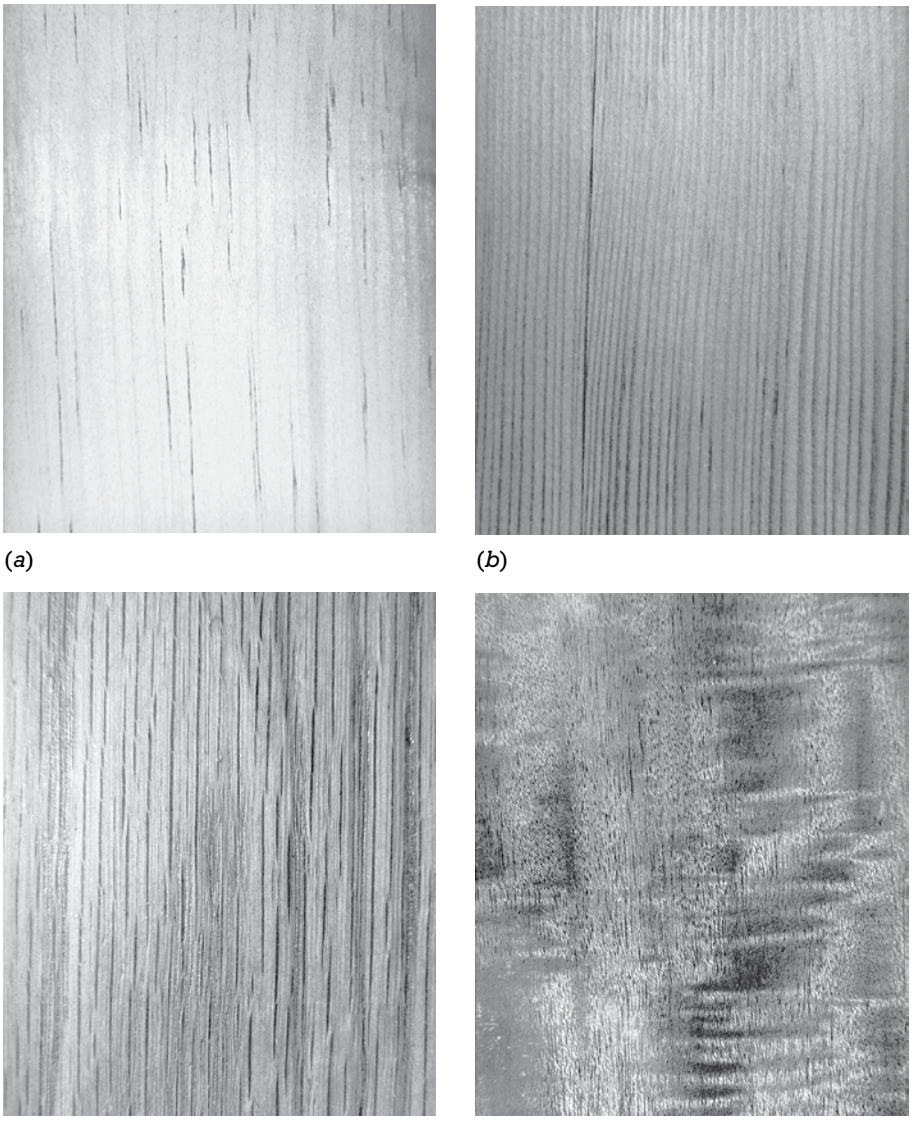


FIGURE 3.4
Grain figures of two softwoods (*a*, *b*) and two hardwoods (*c*, *d*). (*a*) The uniform cell structure in sugar pine makes an almost invisible grain structure except for scattered resin ducts; (*b*) vertical-grain Douglas fir shows very pronounced dark bands of summerwood; (*c*) red oak exhibits large open pores amid its fibers; (*d*) quartersliced mahogany veneer has a pronounced "ribbon" figure caused by varying light reflections off its fibers. *(Photos by Edward Allen.)*

USES	SOFTWOODS	HARDWOODS
Structural framing, structural wood panels	Douglas fir, larch, Southern pine, Western hemlock, white spruce, and other firs, pines, and spruces	
Trim, paneling, cabinetwork, furniture, flooring	Bald cypress, Douglas fir, redwood, Sitka spruce, white pine, yellow cedar, and other cedars, firs, and pines	American beech, American chestnut, birch, black cherry, black walnut, hard maple, mahogany, pecan, red oak, teak, white oak, white poplar, and others
Decay-resistant exterior shingles, siding, decking	Bald cypress, redwood, yellow cedar, and other cedars	Ipe

FIGURE 3.5
Common wood species used in building construction in North America.

Sustainability and Wood

Building and Material Life-Cycle Impacts

- Though precise estimates vary, wood buildings are typically judged to have lower embodied energy and global warming impacts than steel or concrete buildings of comparable size.
- For example, one study calculates that supporting 1 square meter (10 square feet) of floor area with wood structural framing requires roughly 80 MJ (80,000 BTU) of energy and accounts for 4 kg (9 pounds) of CO_2 emissions. In comparison the same floor area framed in structural steel requires 500 MJ (500,000 BTU) of energy and accounts for 40 kg (90 pounds) of CO_2 emissions, and concrete, 300 MJ (300,000 BTU) of energy and 30 kg (70 pounds) of CO_2 emissions.
- An industry-average EPD reports the following cradle-to-gate impacts per cubic meter (630 board feet) of processed softwood dimension lumber:

Nonrenewable primary energy consumption	1200 MJ (1.2 million BTU)
Global warming potential (carbon sequestration excluded)	73 kg (160 lb) CO_2 eq.
Fresh water consumption	90 L (24 gal)

- The same EPD also reports that a cubic meter of softwood dimension lumber contains roughly 220 kg (480 pounds) of sequestered carbon, with a CO_2 eq. (equivalent) global warming potential of 790 kg (1800 pounds). Over a 100-year time span, assuming typical reuse and disposal patterns, this will decline to approximately 480 kg (1100 pounds) CO_2 eq. while 310 kg (380 pounds) CO_2 eq. will have been returned to the atmosphere through burning or decay.
- Kiln drying requires large amounts of fuel and accounts for the largest share of energy consumption in lumber production. However, when kilns are fueled with wood waste products rather than nonrenewable fossil fuels, global warming impacts are reduced.
- Manufactured wood products typically have somewhat higher environmental impacts than solid lumber products, due to the addition of fossil fuel–based resins and adhesives, and the added energy required to complete the processing and fabrication of such components.
- When a wood building is demolished, large members can be recycled directly into the frame of another building, sawn into new boards, or shredded as raw material for other uses. There is an established industry whose business is purchasing and demolishing old barns, mills, and factories and selling their timbers, planks, flooring, and siding as *reclaimed lumber*. Any such wood recycling diverts these materials from the waste stream and further delays the return of sequestered carbon to the atmosphere.

Material and Production Attributes

- Wood is the only major structural material that is renewable. In North America, the area of forested land has remained essentially unchanged for more than 100 years, while the volume of wood grown per acre has increased over the same period.
- Since 1985, the rate of sawn lumber recovery from logs has increased by more than 25 percent while waste

Lumber

Sawing

The production of *lumber*—lengths of squared wood for use in construction—begins with the felling of trees and the transportation of the logs, or *roundwood*, to a sawmill (Figure 3.6). Sawmills range in size from tiny family operations to giant semiautomated factories. But the process of lumber production is much the same regardless of scale. Each log is stripped of its bark then passed repeatedly through a large headsaw, which may be either a circular saw or a bandsaw, to reduce the log to untrimmed slabs of lumber. The sawyer judges (with the aid of a computer in the larger mills) how to obtain the maximum marketable wood from each log and uses hydraulic machinery to rotate and advance the log in order to achieve the required succession of cuts. As the slabs fall from the log at each pass a conveyor belt carries them to smaller saws, where they are reduced to square-edged pieces of the desired widths (Figure 3.7). The sawn pieces at this stage of production have rough-textured surfaces and may vary slightly in dimension from one end to the other.

As a log is sawn, the positioning of the saw relative to the log and the sequencing of cuts determines the grain orientation within the finished lumber pieces. For softwoods, lumber is described as either plainsawn or quartersawn. With *plainsawn* lumber, significant portions of the growth rings are oriented roughly flat relative to the board's broader face. Plainsawing requires the least repositioning of the log during sawing and produces the maximum yield of useful pieces, making it the most economical sawing

products from mill operations have fallen from more than 10 percent to less than 1 percent of harvested log mass.

- In comparison to solid lumber, manufactured wood products efficiently utilize more of the wood fiber in a tree and can be produced from younger-growth forests.
- The increased use of recovered wood fiber, agricultural fibers, and bamboo in the manufacture of structural and finish products helps to reduce the demand for newly harvested wood.

Unhealthful Materials and Emissions

- The LEED rating system awards points for selection of wood products manufactured with adhesives or resin that comply with *ultra-low-emitting formaldehyde* (*ULEF*) standards established by the California Air Resources Board (CARB) or that are made with no added formaldehyde. The Living Building Challenge identifies formaldehyde as a Red List material and has low-emissions criteria similar to those of LEED. See the sidebar, "Wood Product Adhesives and Formaldehyde," later in this chapter, for more information about formaldehyde in manufactured wood products.
- In damp locations, molds and fungi may grow on wood members, creating unpleasant odors and releasing spores to which many people are sensitive or allergic.

Responsible Industry Practices and Social Impacts

- Environmental problems often associated with logging of forests include loss of wildlife habitat, reduction in biodiversity, soil erosion, pollution of waterways, and air pollution from machinery exhaust and burning of tree wastes.
- In a clearcut forest, all the harvestable trees in an area are removed at one time, leaving the stumps, tops, and limbs to decay and become compost. New trees are planted and tended until they are ready for harvest, and then the cycle is repeated. In a selectively logged forest, only some trees in a stand are removed at any given time. Selective logging better maintains healthy forest ecosystems. All major sustainable forestry programs allow at least some clearcutting to occur in certified forests, though the extent and criteria vary from one standard to the next.
- Forest Stewardship Council Chain of Custody certified wood is recognized by the LEED and Living Building Challenge rating systems.
- The LEED rating system recognizes bio-based materials certified to the Rainforest Alliance Sustainable Agriculture Standard.
- The mountain pine beetle blight afflicting much of North America's pine forests in the first decades of the 21st century has left large stands of trees that, though dead, remain suitable as an economical source of sound, structural building material. Harvesting and building with this wood removes it from the forests, where it otherwise presents a fire hazard, and prevents its decay.
- The U.S. softwood lumber industry is responsible for more than 200,000 jobs directly related to the manufacture of wood products and many more jobs indirectly related to this activity. Increased use of wood products in construction provides economic benefits to the (mostly rural) communities where wood harvesting, milling, and manufacturing occur.

method. For this reason, most structural lumber is plainsawn. With *quartersawn* softwood lumber, the growth rings are aligned at an angle of approximately 45 degrees or steeper relative to the board's broader face. Quartersawing requires more handling of the log during sawing, produces smaller pieces from a log of the same size, and generates greater waste. But it also results in boards that are more dimensionally stable and have a more visually pleasing grain figure. Quartersawn flooring and exterior siding wear better, as there are no broad areas of soft springwood exposed on the face as there are in plainsawn lumber. In some wood species, quartersawn lumber also holds paint better than plainsawn. Quartersawn softwood lumber is used for flooring, trim, siding, and other types of finish woodwork, where its advantages justify the added expense. Plainsawn and quartersawn lumber may also be referred to as *flat-grain* or *vertical-grain*, respectively, reflecting the patterning of the grain on the board's broader face produced by each of these sawing methods (Figures 3.8 and 3.9).

Hardwoods may be quartersawn, riftsawn, or plainsawn. A quartersawn board has growth rings aligned at an angle of approximately 60 degrees or greater to the board's broader face. Quartersawing produces a straight, tightly spaced grain pattern. And in woods with strong ray structures, such as oak, this cut produces an often-sought-after appearance in which the rays appear prominently as contrasting elements, called *flecks* or *flakes*, within the figure. With *riftsawn* lumber, growth rings align at an angle of roughly 30 to 60 degrees to the board's broader face. This cut also produces a tightly spaced and uniform grain figure, but without expression of the

wood's ray structure. As with softwood lumber, these cuts are reserved for uses where the better appearance, durability, and stability of the finished boards justify the greater cost in comparison to plainsawn boards.

Seasoning

The amount of water present in wood is called its *moisture content* (*MC*) and is described as the weight of the water in the wood as a percentage of the weight of the dry wood. To determine moisture content, wood is first weighed in its wet state. It is then placed in an oven, dried until all moisture in the wood has evaporated, and weighed again. Moisture content is then calculated as follows:

$$MC = \frac{Weight, wet - Weight, oven\ dry}{Weight, oven\ dry} \times 100$$

The moisture content of growing wood can vary from about 30 percent to 200 percent or more. After a tree is cut, water starts to evaporate from the wood. First to leave is the *free water*, or water stored within the cell cavities. The evaporation of free water has little effect on the physical properties of the wood, other than to lighten it. When the free water is gone, only *bound water*, or water held more tightly within the cellulose of the cell walls, remains. This moisture condition is termed the wood's *fiber saturation point* and averages around 30 percent. Reductions in moisture content below the fiber saturation point have significant effects on the mechanical properties of the wood, causing it to shrink and gain strength and stiffness. Eventually, as water continues to evaporate from the wood, the wood arrives at a moisture content that brings it into equilibrium with its ambient surroundings—dryer, for wood used indoors or in dry outdoor climates, and more moist, for wood used outdoors and in higher humidity or wetter climates. This final moisture condition is called the *equilibrium moisture content* (*EMC*) of the wood.

Figure 3.6
Loading logs onto a truck for their trip to the sawmill. *(Photo by Donald K. O'Brien.)*

Figure 3.7
Sawn lumber is sorted into stacks according to its cross-sectional dimensions and length. *(Courtesy of Western Wood Products Association.)*

In North America, the equilibrium moisture content for exterior wood averages around 12 percent, and for interior wood, 8 percent. These values are lower for dry climate areas and higher for more humid areas. Ideally, wood would always be close to its anticipated final equilibrium moisture content when installed in a building. In this way, distortions or movement caused

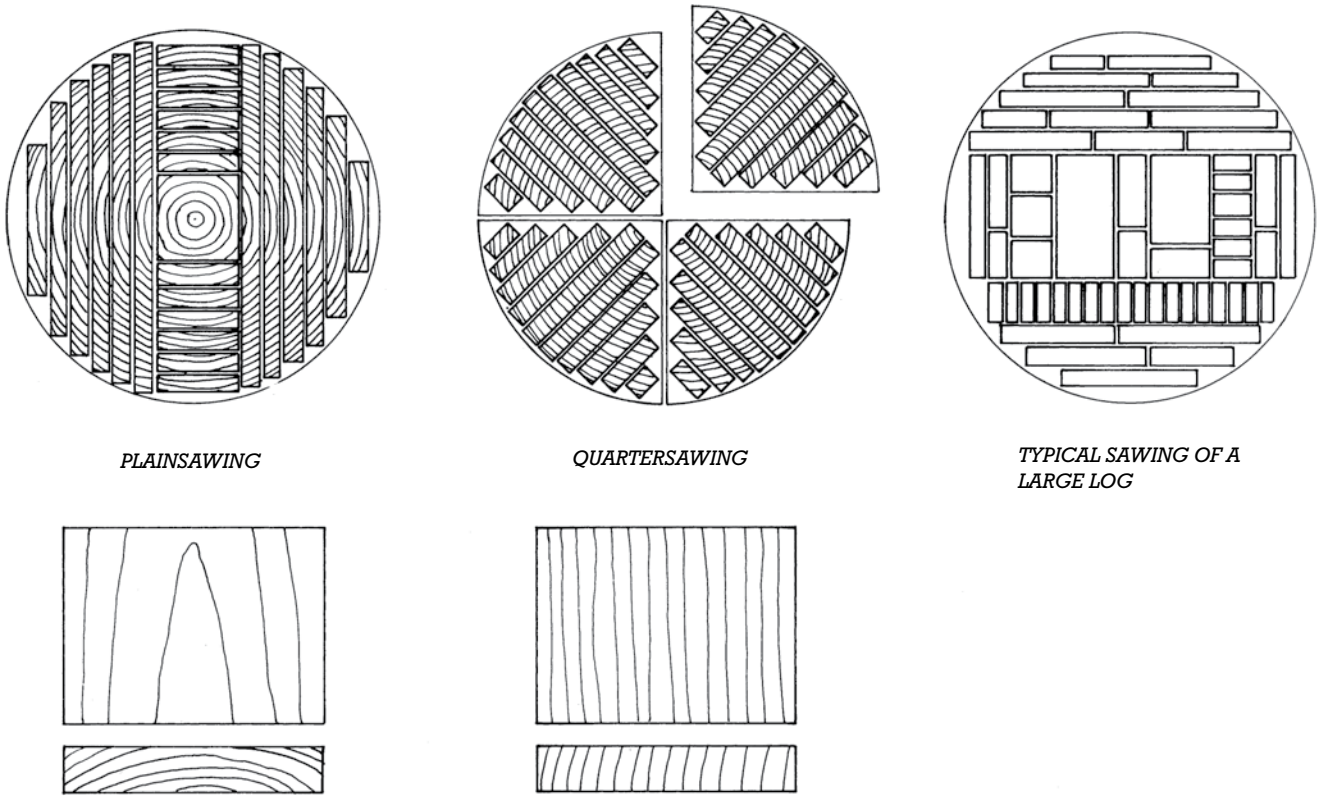


FIGURE 3.8
***Left*: Plainsawing produces boards with a broad, irregular grain figure. *Middle*: Quartersawing produces a more tightly spaced, regular grain structure. *Right*: A large softwood log may be sawn to produce a variety of sizes and cuts of lumber, some large timbers, some plainsawn dimension lumber, and, in the horizontal row of small pieces seen just below the heavy timbers, some pieces of vertical-grain decking.**

FIGURE 3.9
***Left*: Vertical-grain Douglas fir. Tightly spaced growth rings and quartersawing produce a distinctive, consistent grain pattern on the face of this piece of lumber. *Right*: Flat-sawn pine. More widely spaced growth rings and plainsawing produce a broader, more irregular grain figure.** *(Photo by Joe Iano.)*

by subsequent changes in moisture content would be minimized. However, drying wood takes time and energy. So, in practice, the extent of drying, or *seasoning*, varies with the application. Standard framing lumber is seasoned to a moisture content of 19 percent at the mill. For structural applications that require better control of wood shrinkage, lumber seasoned to a moisture content of 15 percent, labeled "MC 15," is produced. Woods used for finish carpentry and fine woodwork are seasoned to within a few percentage points of their expected final equilibrium moisture contents prior to installation.

Most lumber is seasoned at the sawmill, as the lighter weight of dried lumber makes it less expensive to ship. Seasoning may be done by air-drying in loose stacks for a period of months or within kilns under controlled conditions of temperature and humidity for a period of days (Figures 3.10 and 3.11). Though it requires more energy, *kiln drying* is generally preferred to *air drying* because it can be done faster, and it produces lumber with fewer distortions and more uniform quality. Larger wood members may also be seasoned in radio frequency/vacuum kilns that rely on lowered atmospheric pressure and electromagnetic radiation for efficient and uniform drying. In areas where trees are harvested and milled close to their final point of use, lumber may delivered to the construction site *green* and allowed to season in place. Larger-dimension timbers, which are very slow to dry, are also frequently allowed to complete their seasoning in place.

Nor do I ever come to a lumber yard with its citylike, graduated masses of fresh shingles, boards and timbers, without taking a deep breath of its fragrance, seeing the forest laid low in it by processes that cut and shaped it to the architect's scale of feet and inches. . . .

—Frank Lloyd Wright, *Architectural Record,* December 1928

Wood does not shrink and swell uniformly with changes in moisture content. Moisture shrinkage along the length of the log (*longitudinal shrinkage*) is negligible for practical purposes. Shrinkage in the radial direction (*radial shrinkage*) is many times larger by comparison, and shrinkage around the circumference of the log (*tangential shrinkage*) is larger again by half or more (Figure 3.12). If an entire log is seasoned before sawing, it will shrink very little along its length, but it will grow noticeably smaller in diameter, and the difference between the tangential and radial shrinkage will cause it to check, that is, to split open along its length (Figure 3.13).

When lumber is sawn from the log, its position in the log determines in large part how it will distort as it dries. Figure 3.14 shows how the differences between tangential and radial shrinkage cause this to happen. These effects are pronounced and are readily predicted and observed in everyday practice.

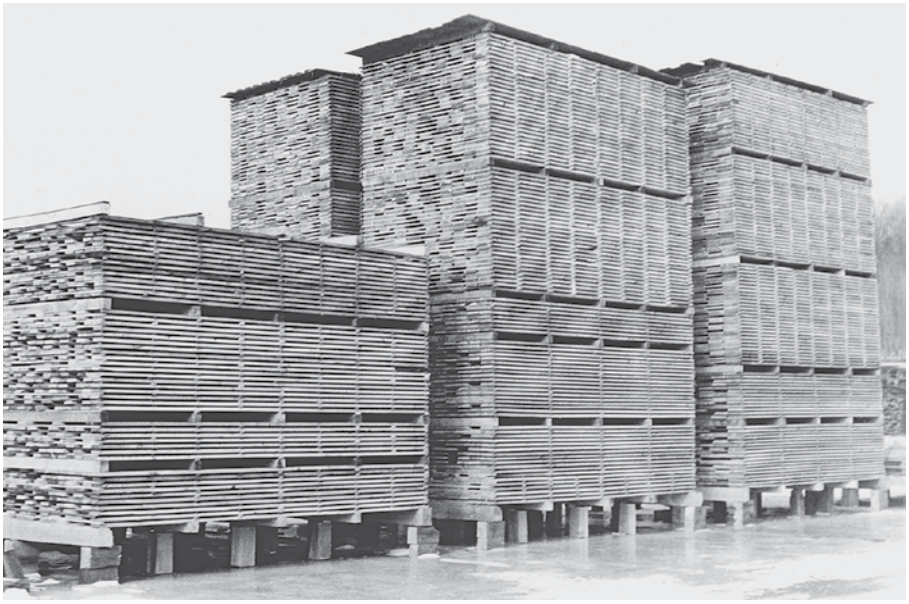


Figure 3.10
For proper air drying, lumber is supported well off the ground. The stickers, which keep the boards separated for ventilation, are carefully placed above one another to avoid bending the lumber, and a watertight roof protects each stack from rain and snow. *(Courtesy of Forest Products Laboratory, Forest Service, USDA.)*

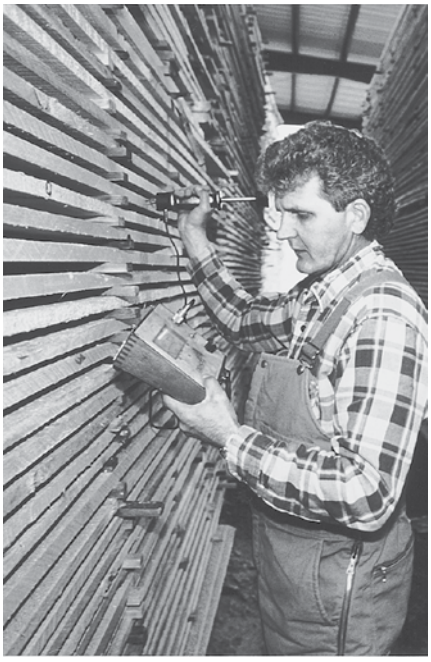


Figure 3.11
Measuring moisture content in boards in a drying kiln. *(Courtesy of Western Wood Products Association.)*

The shrinkage behavior of woods cannot be ignored in building design. For example, in constructing building frames of plainsawn lumber, a simple distinction is made between parallel-to-grain shrinkage, which is negligible, and perpendicular-to-grain shrinkage, which is considerable. The difference between radial and tangential shrinkage is mostly ignored because the orientation of the annual rings in plainsawn lumber is random and unpredictable. As we will see in Chapter 5, wood building frames should be designed to equalize the amount of wood supporting building loads perpendicular to grain from one side of the structure to the other, to avoid different amounts of shrinkage from one side to the other and the tilting of floors or tearing of wall finish materials that this can cause.

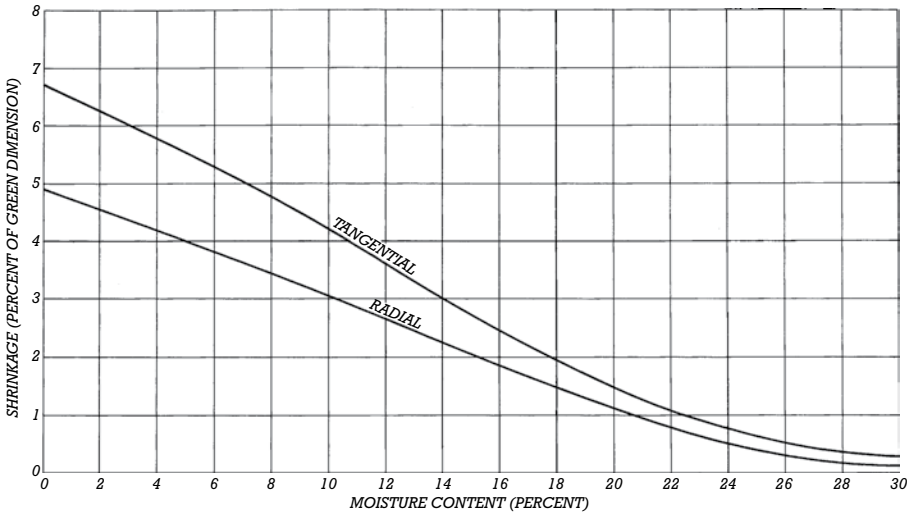


FIGURE 3.12
Shrinkage of a typical softwood with decreasing moisture content. Longitudinal shrinkage, not shown on this graph, is so small by comparison to tangential and radial shrinkage that it is of no practical consequence in wood buildings. *(Courtesy of Forest Products Laboratory, Forest Service, USDA.)*

Surfacing

Lumber used in building construction is normally *surfaced* to make it smooth, more dimensionally precise, and safer to handle. Surfacing is done by high-speed machines, called *planes*, whose rotating blades smooth the surfaces of the piece and round the edges slightly. Most lumber is *surfaced four sides* (*S4S*)—surfaced on all four sides—but hardwoods are often *surfaced two sides* (*S2S*), which leaves the two rougher edges to be finished by the woodworker. Rough (*unsurfaced*) lumber is also available commercially. For example, planking for temporary scaffolding benefits from the rougher texture of unsurfaced lumber (making it less slippery when wet) and from the slightly greater overall dimensions of the plank (making it slightly stronger and stiffer).

Lumber is usually seasoned before it is surfaced, which allows the planing process to remove some of the distortions that occur during seasoning. For some framing lumber, though, this order of operations is reversed. The designation *S-DRY* on a lumber grade stamp indicates that the piece was surfaced when in a seasoned (dry) condition, and *S-GRN* indicates that it was surfaced when green.

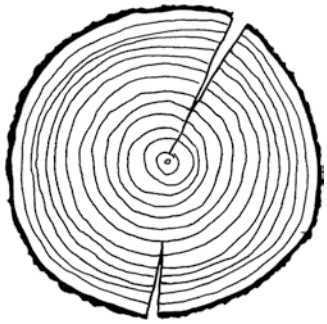


FIGURE 3.13
Because tangential shrinkage is so much greater than radial shrinkage, high internal stresses are created in a log as it dries, inevitably resulting in the formation of radial cracks called *checks*.

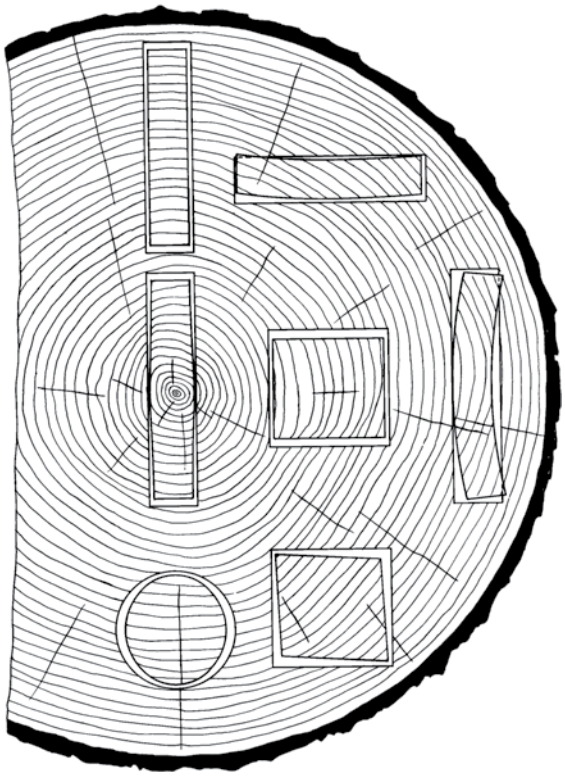
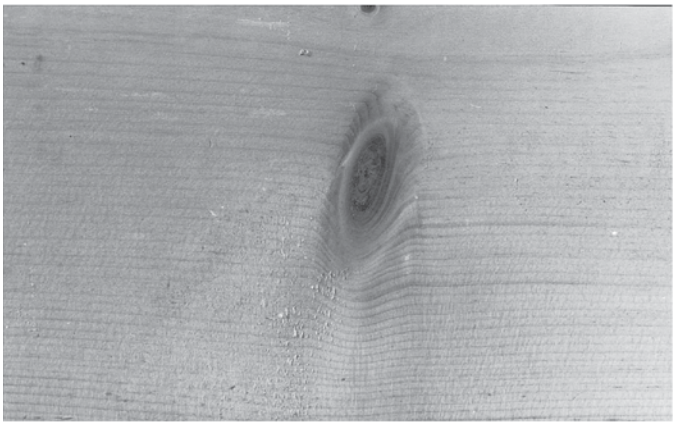


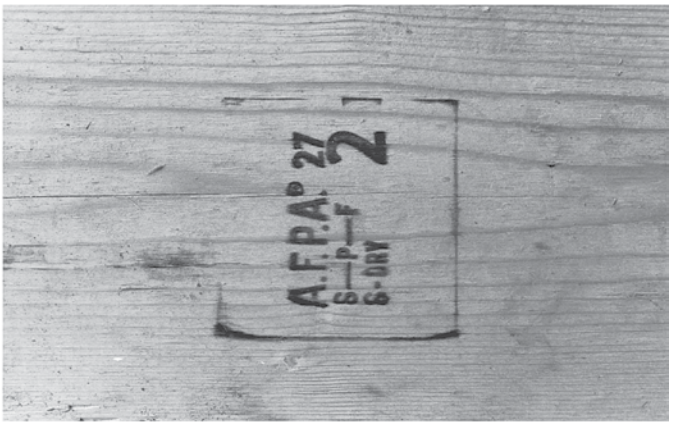
FIGURE 3.14
The difference between tangential and radial shrinkage also produces seasoning distortions in lumber. The nature of the distortion depends on the position the piece of lumber occupied in the tree. The distortions are most pronounced in plainsawn lumber (*upper right, extreme right, lower right*). *(Courtesy of Forest Products Laboratory, Forest Service, USDA.)*

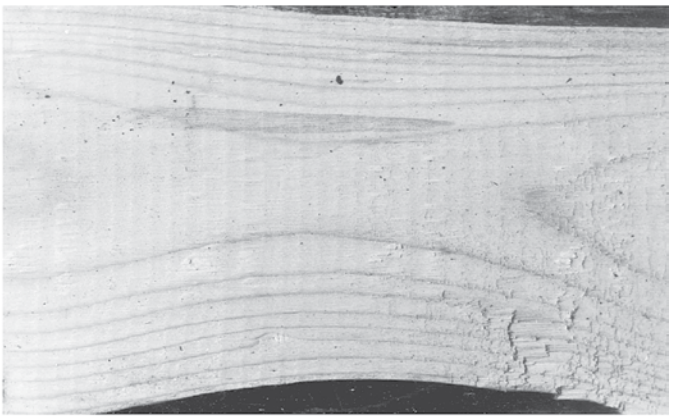
Lumber Defects

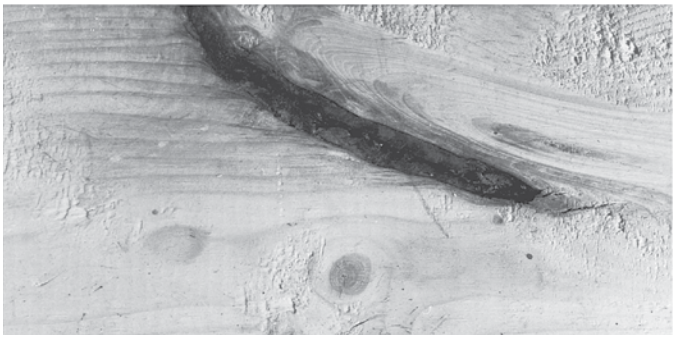
Almost every piece of lumber contains discontinuities in its structure caused by *growth characteristics* of the tree from which it came or *manufacturing characteristics* that were created at the mill (Figures 3.15 and 3.16). Among the most common growth characteristics are *knots*, which are places where branches joined the trunk of the tree; *knotholes*, which are holes left by loose knots dropping out of the wood; *decay*; and *insect damage*. Knots and knotholes reduce the strength of a piece of lumber, make it more difficult to cut and shape, and are often considered detrimental to its appearance. Decay and insect damage that occurred during the life of the tree may or may not affect the useful properties of the piece of lumber, depending on whether the organisms are still alive in the wood and the extent of the damage.

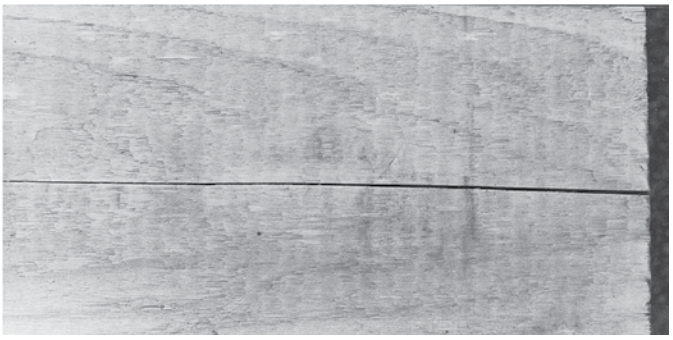
Manufacturing characteristics arise largely from changes that take place during the seasoning process because of the differences in rates of shrinkage with varying orientations to the grain. *Splits* and *checks* are usually caused by shrinkage stresses. *Crooking*, *bowing*, *twisting*, and *cupping* all occur because of nonuniform shrinkage. *Wane* is an irregular rounding of edges or faces that is caused by sawing pieces too close to the perimeter of the log. Experienced carpenters judge the extent of these defects and distortions in each piece of lumber and decide accordingly where and how to use the piece in the building. Checks are of little











consequence in framing lumber, but a joist or rafter with a crook in it is usually placed with the convex edge (the "crown") facing up to allow the floor or roof loads to straighten the piece. Badly bowed wall studs, floor joists, or roof rafters may be straightened by sawing or planing away the crown before being covered by wallboard, subflooring, or sheathing. Badly twisted pieces are put aside to be cut up for blocking. The effects of cupping in flooring and interior baseboards and trim are usually minimized by using well seasoned, quartersawn stock and by shaping the pieces so as to reduce the likelihood of distortion (Figure 3.17).

Lumber Grading

Before each piece of lumber leaves the mill, it is graded either for appearance or structural properties, depending on its intended use. Grading offers the architect and the engineer the opportunity to build as economically as possible by using only as high a grade as is required for a particular use. For example, the main beams or columns of a building may require a stronger, higher structural grade of lumber, while the remainder of the framing members may perform adequately with an intermediate, less expensive grade. For blocking, the least expensive, lowest grade is perfectly adequate. For interior trim that will be coated with a clear finish, a high appearance grade is desirable; for painted trim, a less expensive lower grade will suffice.

FIGURE 3.15
(*Opposite page*) Examples of lumber growth and manufacturing characteristics. In the left-hand column from top to bottom are a knot cut crosswise, a knot cut longitudinally, and a bark pocket. To the right are a gradestamp, wane on two edges of the same piece, and a small check. The gradestamp indicates that the piece was graded according to the rules of the American Forest Products Association, that it is #2 grade Spruce–Pine–Fir, and that it was surfaced after drying. The 27 is a code number for the mill that produced the lumber. *(Photos by Edward Allen.)*

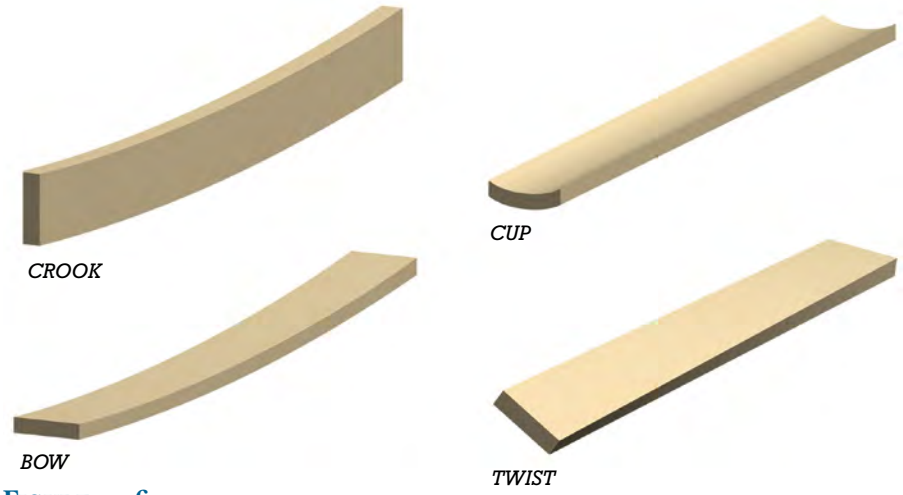


FIGURE 3.16
Four types of seasoning distortions in dimension lumber.

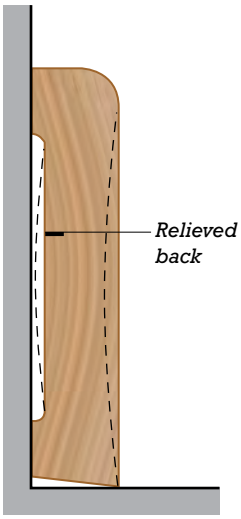


FIGURE 3.17
The effects of seasoning distortions can often be minimized through knowledgeable detailing practices. As an example, this wood baseboard, seen in cross section, has been formed with a relieved back, a broad, shallow groove that allows the piece to lie flat against the wall even if it cups (see broken lines). The sloping bottom on the baseboard ensures that it can be installed tightly against the floor despite the cup. The grain orientation in this piece is the worst possible with respect to cupping. If quartersawn lumber had not been available, the next best choice would have been to mill the baseboard with the center of the tree toward the room rather than toward the wall.

Structural grading is used to rate the strength and stiffness properties of a piece of lumber. It is done either visually or by machine. In *visual grading*, trained inspectors (or, more recently, computerized imaging devices) examine each piece for growth ring density and growth and manufacturing characteristics, judge it according to standard grading rules, and then stamp it accordingly. In *machine grading*, automated devices assess the stiffness, density, or other properties of the wood to derive structural values and apply an appropriate grade stamp. *Machine stress rated* (*MSR*) *lumber*, *machine evaluated lumber* (*MEL*), and *E-rated lumber* are all machine grading processes.

Much structurally graded lumber is rated by *species group* or *species combination*, that is, by collections of individual wood species that are sufficiently similar in their properties that they may be used interchangeably. By allowing the intermingling of similar species within one group, harvesting, production, and distribution costs are reduced. For example, Hem–Fir, one of the highest-volume species groups marketed in North America, may include any combination of California red fir, grand fir, noble fir, Pacific silver fir, Western hemlock, and white fir. Other commonly encountered structural grade species groups include Douglas Fir–Larch, Spruce–Pine–Fir, and Southern pine.

Appearance grading is used to rank the visual qualities of lumber intended for flooring, trim, cabinetry, and other nonstructural finish uses. Naturally, it is done visually, with boards having the fewest knots, checks, splits, staining, and other defects receiving the highest grades.

Figure 3.18 outlines a typical structural grading scheme for framing lumber. For example, framing lumber for a house or other small building may be ordered as "#2 and better" (a mixture of #1 and #2 grades) for floor joists and roof rafters and as Stud grade for wall framing.

Grade	Uses
Select Structural No. 1 & Better No. 1 No. 2 No. 3	Structural applications where highest design values are needed, such as joists, rafters, headers, beams, and trusses
Construction Standard Utility	Medium-to-low strength applications, such as wall framing, plates, sills, cripples, blocking, etc.
Stud	All-purpose, medium strength studs

FIGURE 3.18

Standard structural grades for Western softwood framing lumber. For each species of wood, the allowable structural stresses for each of these grades are tabulated in the structural engineering literature, a few examples of which are shown in Figure 3.19.

	Allowable compressive stress, parallel to grain		
Species Group	**Stud Grade**	**No. 2**	**Select Structural**
Spruce–Pine–Fir	760 psi (5.3 MPa)	1320 psi (9.1 MPa)	1610 psi (11 MPa)
Hem–Fir	840 psi (5.8 MPa)	1495 psi (10 MPa)	1725 psi (12 MPa)
Southern Pine	850 psi (5.9 MPa)	1450 psi (10 MPa)	1900 psi (13 MPa)
Douglas Fir–Larch	895 psi (6.2 MPa)	1555 psi (11 MPa)	1955 psi (13 MPa)

FIGURE 3.19

Comparative allowable stresses (with factors of safety applied) for four common species groups and three structural grades. These figures are for 2 × 4 lumber, compressive stress, parallel to the grain of the member.

Structural Properties of Lumber

The strength of a piece of wood varies with the direction in which the load acts in relation to the grain of the wood, the duration of the stress, and the species and grade of the wood. For example, the tensile strength of a wood member with the load applied parallel to its grain may be as much as 10 to 20 times greater than its strength with the load applied across the grain. In any given orientation, wood is also normally stronger in compression than in tension, and stronger under short-term loading than under longer-duration or permanent loads. Some comparative strengths of selected wood species and grades are listed in Figure 3.19.

Figure 3.20 compares the structural properties of framing lumber to those of some other common structural materials: brick masonry, steel, and concrete. Of the four, only wood and steel have useful tensile strength. On an equal weight basis, the compressive strength of an average structural grade wood is roughly half that of steel and two to three times that of concrete or brick masonry.

When designing a wooden structure, the architect or engineer determines the maximum stresses expected to occur in the various structural members and selects the appropriate species groups and grades from which to build. In a given locale, a limited number of species and grades are usually available in retail lumberyards, and it is from these that the selection is made. It is common practice to use a stronger but more expensive species group (a high grade of Douglas Fir–Larch or Southern pine, for example) for highly stressed major members and to use a weaker, less expensive group (such as a medium grade Hem–Fir or Spruce–Pine–Fir) for other parts of the structure. Within each species group, the designer selects grades based on published tables of allowable stresses. The higher the structural grade, the higher the allowable stress. But the lower the grade, the less costly the lumber.

Other factors that influence the usable strength of wood include the temperature and moisture conditions under which it serves, and the size and shape of the piece. Chemical treatments applied to wood to increase its resistance to decay or fire may also reduce its strength slightly. All these factors are taken into account when engineering a building structure of wood.

Lumber Dimensions

Lumber sizes in North America are given as *nominal sizes* in inches, such as 1 × 2 ("one by two"), 2 × 10, and so on. At one time, sawn lumber may have approached these actual dimensions. Today, however, subsequent to sawing, seasoning, and surfacing, true sizes are less. By the time a kiln-dried 2 × 4 reaches the lumberyard, for example, its *actual size* is approximately 1½ × 3½ inches (38 × 89 mm).

The difference between nominal and actual size varies depending on the lumber product category and the size of the piece. Common product types include boards, dimension lumber, and timbers. *Boards* are less than nominal 2 inches in their least dimension. For example, 1 × 2, 1 × 6, ¾ × 4 are boards because the smaller nominal dimension is less than 2. *Dimension lumber* is from nominal 2 to 4 inches in its least dimension, including, for example, 2 × 4, 3 × 10, and 4 × 4. *Timbers* are nominal 5 inches or more in their least dimension, for example, 5 × 10 or 6 × 6. The relationships between nominal size and actual size for boards and dimension lumber are given in Figure 3.21, and for timbers, in Figure 3.22.

Material	Strength in Tension	Strength in Compression	Modulus of Elasticity	Density
Wood (framing lumber)	270–4100 psi (1.9–28 MPa)	1400–4400 psi (9.7–31 MPa)	1,100,000–1,900,000 psi (7600–13,000 MPa)	27 pcf (430 kg/m^3)
Brick masonry (including mortar, unreinforced)	30–80 psi (0.21–0.55 MPa)	1000–4000 psi (6.9–28 MPa)	800,000–3,000,000 psi (5500–21,000 MPa)	120 pcf (1900 kg/m^3)
Structural steel alloys	60,000–90,000 psi (415–620 MPa)	60,000–90,000 psi (415–620 MPa)	29,000,000 psi (200,000 MPa)	490 pcf (7800 kg/m^3)
Concrete (unreinforced)	300–700 psi 2.1–4.8 MPa	3000–6000 psi (20–40 MPa)	2,000,000–6,000,000 psi (14,000–41,000 MPa)	145 pcf (2300 kg/m^3)

Figure 3.20

Comparative ultimate strength properties of four common structural materials: wood (*shaded row*), brick masonry, steel, and concrete. Wood values are for stresses parallel to the grain of the wood.

To distinguish between nominal and actual size, nominal size is written without any dimension, for example, 2 × 10, whereas dimensions are included when describing actual sizes, such as 1½ × 9¼ inches or 38 × 235 mm. When working in metric units, only actual sizes are used.

Anyone who designs or constructs wooden buildings soon commits the most commonly encountered nominal and actual size relationships to memory. Because of changing moisture content and manufacturing tolerances, however, it is never wise to assume that a piece of lumber will conform precisely to its expected dimensions. Wood members vary in size seasonally with changes in temperature and humidity. And members in older buildings may have been manufactured to full nominal dimensions or to earlier standards of actual dimensions such as 1⅝ inches or 1¾ inches (41 or 44 mm) for a nominal 2-inch member.

Dimension lumber is supplied in 2-foot (610-mm) increments, most commonly in lengths between 8 and 16 feet (2.44 to 4.88 m). For some sizes, pieces as long as 24 feet (7.32 m) may be available.

In North America, lumber is priced by the *board foot*, a measurement based on nominal (not actual) dimensions. A board foot of lumber is defined as a solid volume 12 square inches in nominal cross-sectional area and 1 foot long. For example, a 1 × 12 or 2 × 6, 10 feet long, contains 10 board feet. A 2 × 4, 10 feet long, contains 6.67 board feet [(2 × 4)/12 × 10 = 6.77], and so on. Prices of dimension lumber and timbers in North America are usually quoted on the basis of dollars per thousand board feet (abbreviated MBF or MBFM). In other parts of the world, lumber is sold by the cubic meter based on actual sizes. There is no universal conversion between board feet and cubic meters. This is, in part, because of the discrepancy between nominal and actual sizes on which the two measurements are based. In addition, when these measurements are applied to whole logs, cubic meter measurement rules include all usable wood product (sawn lumber, wood chips, and sawdust) that can be extracted from the log, while board feet measurements apply to only the volume of recoverable sawn lumber.

The production of softwood lumber in North America is governed by the American Softwood Lumber Standard PS 20. This standard addresses lumber sizes, property relationships between green and dried lumber, methods for determining structural design values, nomenclature, inspection, grading, and more. The National Hardwood Lumber Association (NHLA) Grading Rules play a similar role for the governance of hardwood production in North America.

Boards and Dimension Lumber

Nominal Size	Actual size
1	¾" (19 mm)
5/4	1" (25 mm)
6/4	1¼" (32 mm)
2	1½" (38 mm)
3	2½" (64 mm)
4	3½" (89 mm)
5	4½" (114 mm)
6	5½" (140 mm)
8	7¼" (184 mm)
10	9¼" (235 mm)
12	11¼" (286 mm)
Over 12	¾" (19 mm) less

FIGURE 3.21
Nominal and actual sizes for boards and dimension lumber. For example, the actual size of a 1 × 4 board is ¾" × 3½" (19 x 89 mm), or of 2 × 8 dimension lumber, 1½" × 7¼" (38 x 184 mm).

Timbers

Nominal Size	Actual Size
5	4½" (114 mm)
6	5½" (140 mm)
8	7½" (190 mm)
10	9½" (241 mm)
12	11½" (292 mm)
Over 12	½" (13 mm) less

FIGURE 3.22
Nominal and actual sizes for timbers. For example, the actual size of a 6 × 8 is 5½" × 7½" (140 × 190 mm). Unlike boards and dimension lumber, nominal sizes 8 inches and greater are reduced by ½" (13 mm) rather than ¾" (19 mm). Timbers are also more commonly shipped unseasoned, and therefore may be expected to shrink more in service than boards and dimension lumber.

Veneer

Wood produced in very thin sheets (about 1/8 inch, or 3 mm, in thickness or less) is called *veneer*. *Rotary-cut* or *rotary-sliced veneer* is produced by inserting a log into a large *lathe* and spinning the log against a long knife edge (Figure 3.23). As the knife moves steadily into the log, a continuous strip of veneer is peeled away, much as paper is unwound from a roll. Rotary-cut veneer is analogous to plainsawn lumber: It is the least expensive cut to produce and finds its greatest use in structural applications where appearance is not a primary concern. Common applications for rotary-cut veneer are in the manufacture of structural plywood panels, laminated veneer lumber, and parallel strand lumber, products explained in more detail later in this chapter.

Sliced veneer is produced by pressing a log against a knife and slicing off successive individual sheets, each only as wide as the section of log. (Or, veneer may be *sawn* in a similar manner.) Veneer slicing and sawing are more expensive processes than rotary slicing, but they also produce veneers with grain patterns considered more attractive for fine woodwork. For this reason, hardwood veneers used in fine woodworking applications are commonly produced by one of these methods.

The log from which veneer is taken is called a *flitch*. In fine paneling, cabinetry, or other veneered applications, all the veneers may be required to come from a single flitch, to maintain uniformity of appearance among them. Veneers from a flitch can also be *sequenced*, that is, arranged in the finished work in the same order in which they came from the log, so that grain patterns on adjacent pieces match as closely as possible.

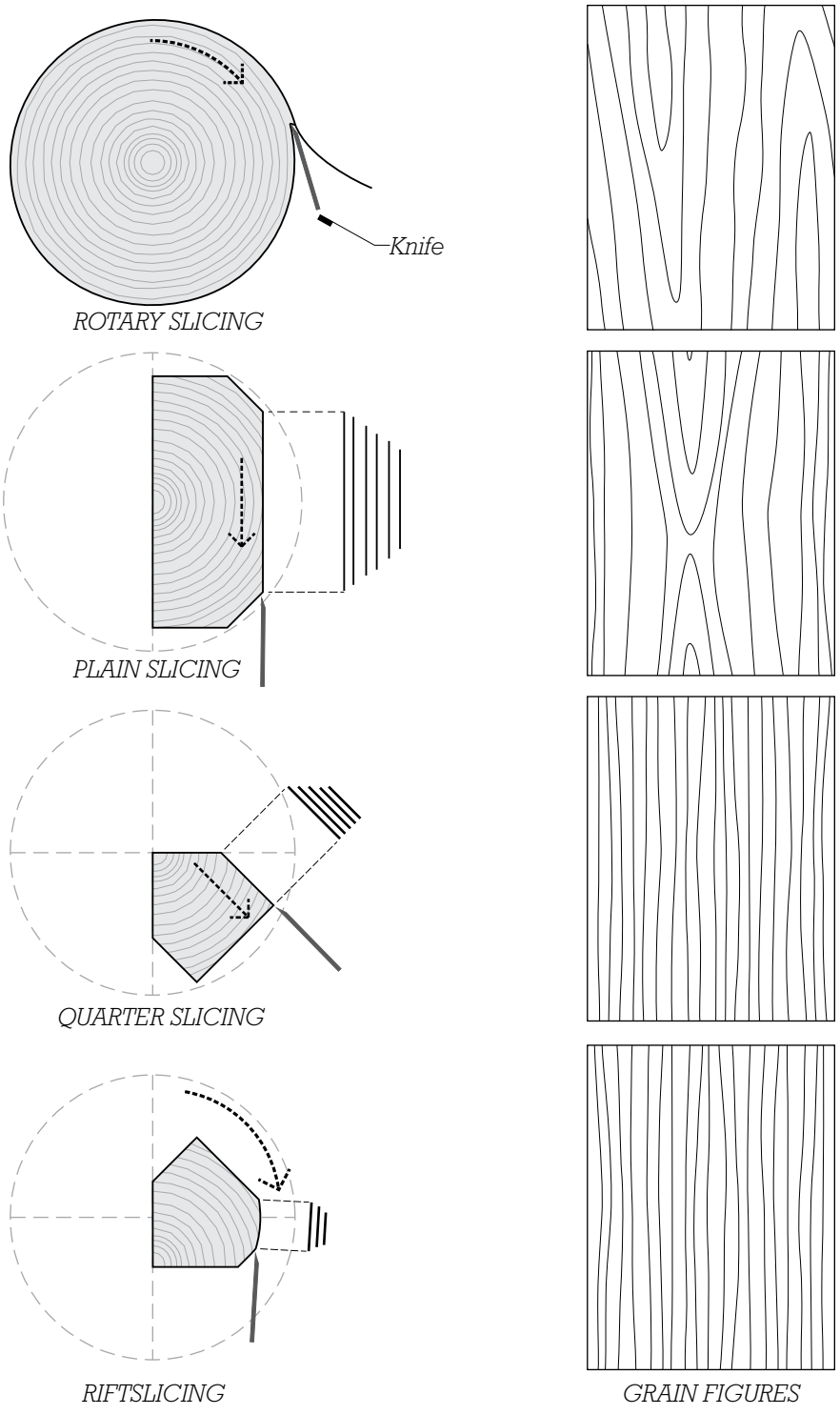


FIGURE 3.23
Veneers for structural panels are rotary-sliced, which is the most economical method. For better control of grain figure in veneers destined for finish woodwork, logs may be *plainsliced*, *quartersliced*, or *riftsliced*. Like quartersawn and riftsawn hardwoods, both of these methods produce veneers with attractive, closely spaced, uniform grain patterns. Riftslicing is used to produce veneers without flecks from woods with pronounced ray structures. (Flecks are not shown in these diagrams.)

Wood Products

Much of the wood used in modern building construction is processed into manufactured products, rather than used directly as sawn lumber. Manufactured products can exceed the structural efficiency and quality of sawn lumber. They can overcome the size limitations of lumber extracted from the tree. And they make economic use of raw wood materials that previously may have been treated as waste.

As discussed in the following sections, sawn lumber, veneer, strands, flakes, particles, and cellulose fibers can be made into a great variety of structural and nonstructural products with higher strength, improved stability, increased size range, and greater diversity of other properties than are available from traditional sawn lumber.

Figure 3.24
Glue-laminated wood members, such as the beams and posts seen here, can be produced in larger sizes, longer lengths, and with higher strengths than solid sawn lumber. *(Photo by Joseph Iano.)*

Glue-Laminated Wood

Large wood structural members are produced by gluing together many smaller pieces of dimension lumber, to form *glue-laminated wood* (*GLT*, or *glulam* for short) (Figure 3.24). Any desired size of structural member can be made, up to the capacities of the hoisting and transportation machinery needed to deliver and erect it. Glulams can be fabricated into variety of shapes, such as curves, angles, and lengths that vary in cross section. And glulam quality can be precisely controlled: Defects are removed from the wood pieces from which glulams are assembled. The pieces are seasoned before lamination, reducing the checking and distortion in the finished member that are common with large-dimension solid wood timbers. And the strongest, highest-quality wood pieces can be matched to those parts of the glulam member that will be subjected to the highest in-service internal stresses, while using less costly, lower-strength pieces in other areas.

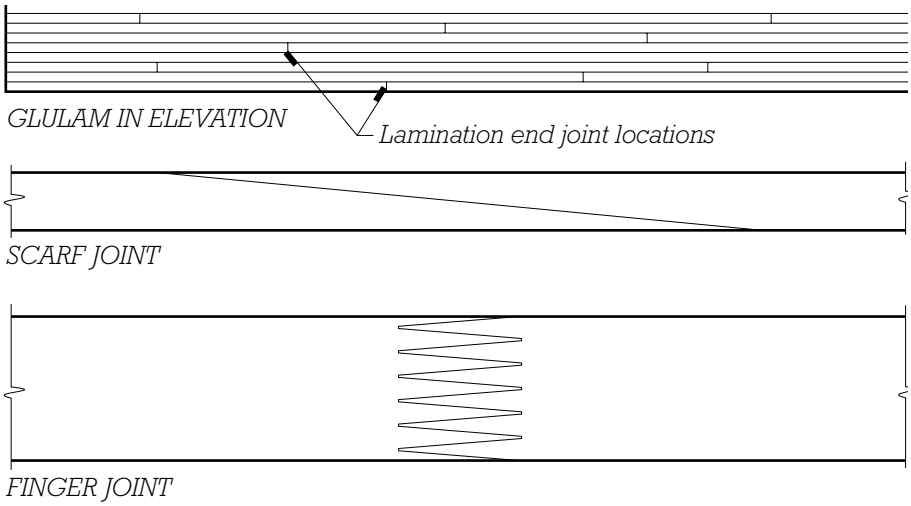


Figure 3.25
(*Top*) A glulam beam shown in elevation, with joint locations indicated diagrammatically. (*Below*) A scarf joint and finger joint shown in detail. Increasing the surface area of jointed material creates a glue joint that is as strong in tension and compression as the wood pieces themselves. The individual pieces of wood are prepared for jointing by high-speed machines that mill the scarf or fingers with rotating cutters of the appropriate shape.

The manufacturing and structural performance of glue-laminated wood members are defined by the ANSI A190.1 and A117 standards. Individual laminations are most commonly 1⅜ or 1½ inches (35 or 38 mm) thick, except in curved members with small bending radii, where stock as thin as ¾-inch (19 mm) may be used. The laminations are seasoned to a moisture content of 16 percent. End joints between individual pieces of lumber are *finger jointed* or *scarf jointed* and glued, creating structural continuity from one piece to the next (Figure 3.25). Typical stock glulam sizes range from 3⅛ to 6¾ inches (79 to 171 mm) in width and from 9 to 36 inches (229 to 914 mm) in depth. For larger buildings, standard sizes up to 14 inches (356 mm) wide and 75 inches (1905 mm) deep are not uncommon. Where glue-laminated beams will be exposed to the weather or to high levels of moisture in the completed construction, suitably moisture-resistant adhesives are used, and laminations may be chemically preservative-treated, as explained later in this chapter, to protect against decay.

FIGURE 3.26
CLT panels, both five-layer and three-layer, stacked on a truck bed. The alternating direction of cross-laminations is clearly visible. To keep the panels dry, they may be sealed, coated in wax, wrapped in plastic, or covered with tarps while being transported. Maximum widths are limited by transportation restrictions.
(Courtesy of Structurlam Inc.)

"Your chessboard, sire, is inlaid with two woods: ebony and maple. The square on which your enlightened gaze is fixed was cut from the ring of a trunk that grew in a year of drought: you see how its fibers are arranged? Here a barely hinted knot can be made out: a bud tried to burgeon on a premature spring day, but the night's frost forced it to desist. . . . Here is a thicker pore: perhaps it was a larvum's nest." . . . The quantity of things that could be read in a little piece of smooth and empty wood overwhelmed Kublai; Polo was already talking about ebony forests, about rafts laden with logs that come down the rivers, of docks, of women at the windows. . . .

—Italo Calvino, *Invisible Cities*, 1978

Hybrid glulam beams substitute laminated veneer lumber (described later in this chapter) for the usually solid wood top and bottom laminations in the beam. Because the highest stresses in the beam occur at these edges, substituting a stronger material in just these locations results in a beam that is stronger and stiffer overall. In *FRP reinforced glulam* beams, structural capacity is increased by gluing a thin strip of high-strength fiber-reinforced plastic (FRP) between the first and second laminations nearest the edge of the beam that acts in tension (usually the lower edge). The fibers used—aramid, glass, carbon, or high-performance polyethylene—are much stiffer and stronger than wood. They are oriented longitudinally and embedded in a plastic matrix before being fabricated into the beam. The result is a savings of 25 to 40 percent in the volume of wood in comparison to a conventional glulam.

Cross-Laminated Timber

Cross-laminated timbers (*CLTs*) are structural panels laminated from solid lumber, with the orientation of members alternating between layers. Finished panels range in size from 2 to 10 feet (0.61 to 2.0 m) in width, 40 to 60 feet (12 to 18 m) in length, and up to 20 inches (510 mm) in thickness. They are used as structural components in walls, floors, and roofs (Figure 3.26).

Cross-laminated timbers are manufactured according to the ANSI/APA PRG 320 standard. Lumber used in the manufacture of the panels is seasoned to a 12 percent moisture content, a relatively low value that helps to minimize dimensional

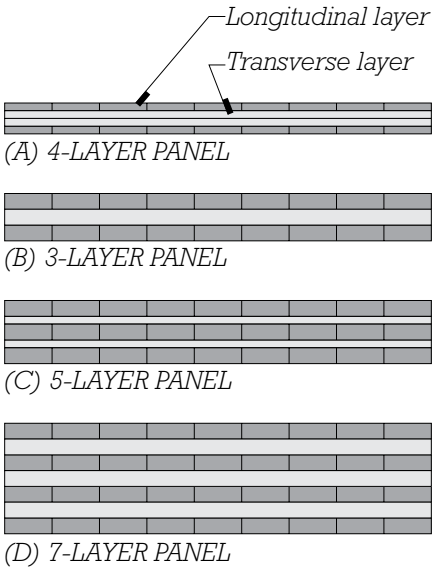


FIGURE 3.27

Examples of CLT panel layups, shown in cross section. (*A*) A four-layer panel with double-core layers. With ⅝-inch (16-mm) layers, total panel thickness is 2½ inches (64 mm). (*B*, *C*) Three-layer panel and five-layer panels, 4⅛ inches (105 mm) and 5⅜ inches (137 mm) thick. (*D*) A seven-layer panel with 1⅜-inch (35-mm) layers, with a total thickness of 9⅝ inches (244 mm).

Interactive Exercise

changes and checking in the finished panels. Prior to assembly, the pieces are planed to a uniform thickness of between ⅜ and 2 inches (16 to 50 mm), a process that also prepares the wood surfaces for a good adhesive bond. Longitudinal members, those oriented parallel to the longer dimension of the panel, are made up from pieces finger-jointed and glued end-to-end. In most panels, only the broader faces of the lumber are planed and glued. However, at additional cost and where needed to meet structural or other performance criteria, the narrow edges of the lumber may be planed, or planed and glued, as well.

Panel assembly consists of stacking perpendicular layers of lumber, with adhesive applied in between each layer. The full stack is compressed in a hydraulic or vacuum press and the adhesive allowed to cure. After assembly, panel faces are planed or sanded to produce a flat surface. Using precision, computer-driven machinery, openings are cut into the panels, edges are machined to final profiles, and other finish operations are completed.

Cross-laminated timbers are assembled from three or more layers, with thicker panels having greater structural capacities and resistance to fire than thinner ones. For example, a simple three-ply wall panel made from 2 × 6 lumber will have longitudinal members in the top and bottom layers, crosswise members in the middle layer, and a finished thickness of approximately 4⅛ inches (105 mm) (Figure 3.27). Panels with an odd number of layers are most common, but even-number layered panels are also feasible. Like glulams, the species and grade of lumber can be varied between layers, reserving higher-strength lumber for the outer layers of the panel where the highest in-service stresses occur. Standard structural grades for CLTs range from E1 (with greatest structural performance) to V3 (lowest performance). E grade panels rely on higher-strength and stiffness machine graded lumber in the laminations running parallel to the longer dimension of the panel. V grade panels use visually graded lumber throughout.

Compared to glulams and large solid timbers, cross-laminated timbers are less subject to change in size with changes in moisture content due to the drier lumber used in their manufacture and the cross-laminated construction of the panel. Compared to concrete, CLTs have a roughly three times greater strength-to-weight ratio. And like some concrete systems, CLTs are also sometimes capable of efficient two-way structural action. The lower weight of CLTs compared to concrete or masonry can result in lower foundation loads and reductions in seismic forces acting on a structure. And the high volume of wood used in CLT structures brings with it the environmental benefits discussed earlier in this chapter, that is, utilization of a renewable resource, low embodied energy, and favorable carbon footprint.

Cross-laminated timbers are a relatively new structural product in the North American building construction market. The number of manufacturers and product availability are growing, and manufacturing technology continues to develop. For example, *mass plywood panels*, similar to CLTs but laminated with wood veneers instead of dimension lumber, have recently come to market. Anticipated future products include high-performance panels fabricated from structural composite lumber products or adhesive-free panels assembled from mechanically interlocking wood members.

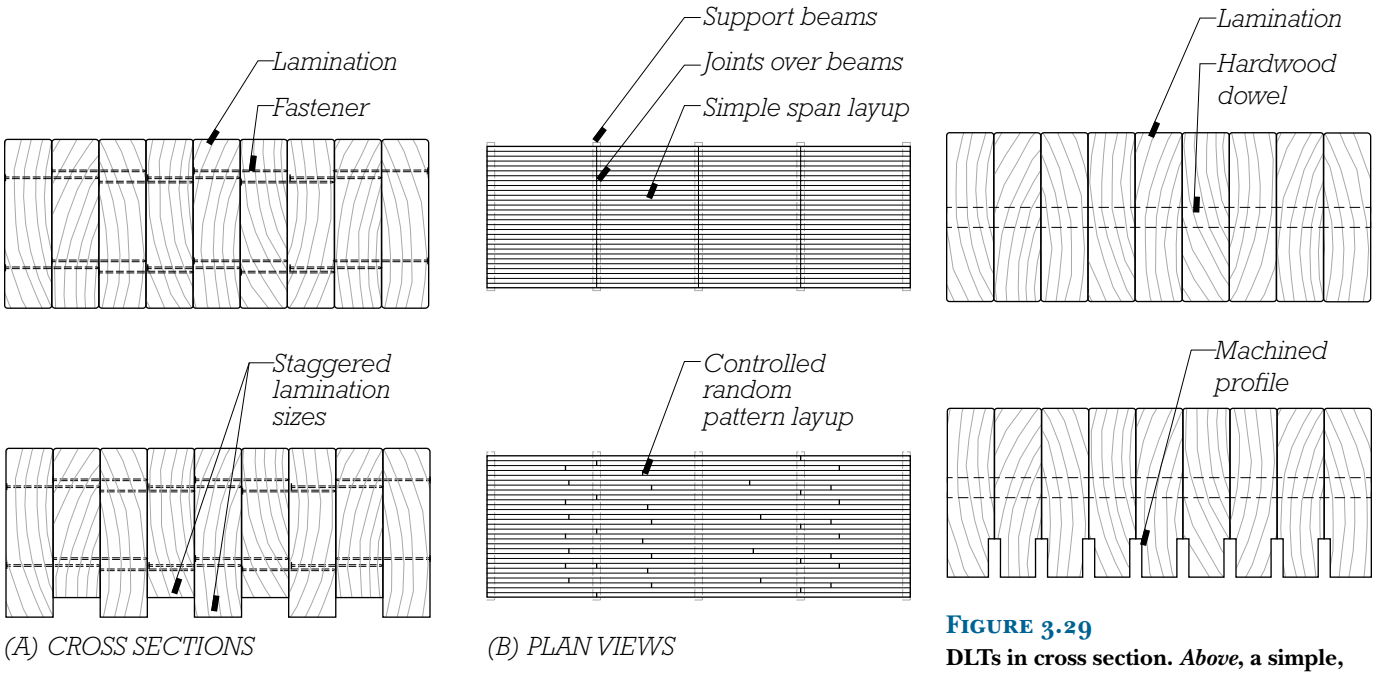


FIGURE 3.28

(*A*) NLTs in cross section. In the lower diagram, laminations alternating in size produce a staggered face profile. Many other profiles are possible. (*B*) NLTs in plan. At top is a simple span layup with laminations spanning only single framing bays and joints occurring over supports. Below, a controlled random pattern layup permits joints to fall between supports, within certain guidelines.

FIGURE 3.29

DLTs in cross section. *Above*, a simple, smooth-faced panel. *Below*, a panel with a machined profile on the bottom face.

Nail-Laminated and Dowel-Laminated Timber

Nail-laminated timber (*NLT*), also called *mechanically laminated timber*, is made from dimension lumber aligned side by side and joined with nails or screws. The use of NLT in North American building construction is over a century old and is now undergoing a resurgence of interest. NLT is most commonly used as floor and roof decking but may also be used for bearing walls and other vertically oriented components. Panels are usually prefabricated offsite but may also be constructed in place. In addition to simple, planar shapes, different face profiles can be created by combining laminations of different sizes or machining lamination edges to various shapes. Or the alignments of lumber pieces may be shifted incrementally in one or both planes of the panel to create simple or compound curvatures (Figure 3.28).

Dowel-laminated timber (*DLT*) is assembled in the same way as NLT, but with wooden dowels used in place of mechanical fasteners. Hardwood dowels, seasoned to a lower moisture content than the laminating lumber, are inserted into holes drilled into the stacked panel laminations. As the moisture content of the dowels rises to reach equilibrium with the surrounding lumber, the dowels swell to form a tight fit. DLTs have the distinction of being made entirely of wood, without adhesives or mechanical fasteners. Like NLTs, DLTs can also be fabricated with many face profiles (Figure 3.29). DLT fabrication requires large machinery to clamp the laminations during assembly, and for that reason is always performed in the factory.

Practical sizes for both panel types are 4 to 12 feet (1.2 to 3.7 m) wide, up to 60 feet (18 m) long, and 3½ to 13¼ inches (89 to 337 mm) deep. NLTs are addressed in current building codes. At this time, there are no North American standards for DLT construction, and building with this panel type requires special engineering analysis and regulatory approval.

Structural Composite Lumber

Structural composite lumber (or *engineered lumber*) products are substitutes for solid lumber made from wood veneers or wood fiber strands and glue. *Laminated strand lumber* (*LSL*) and *oriented strand lumber* (*OSL*) are made from shredded wood strands, coated with adhesive, pressed into a rectangular cross section, and cured under heat and pressure (the wood strands used in the manufacture of LSL are longer than those used in OSL). LSL and OSL are the least strong and least expensive of the composite lumber products. They are used mainly for rim boards and short-span headers. *Laminated veneer lumber* (*LVL*) is made from thin wood veneer sheets, as wide as the member is deep, that are glued and laminated into thicker members. LVL is similar in appearance to plywood except that all the laminations in LVL are oriented with their grain parallel to the long dimension of the beam—that is, there are no crossbands (Figure 3.30). *Parallel strand lumber* (*PSL*) is made from long, thin strips of wood veneer glued and pressed in a process similar to that for LSL and OSL, but with the veneer strips arranged more uniformly parallel than the strands in those other products. PSL is the strongest and most expensive of the composite lumber products (Figure 3.31). LVL and PSL are most commonly used for longer-span headers and floor beams.

Studs and posts may also be made of any of these composite lumber products, and are used to frame especially tall walls, walls with large openings, or wherever else long, straight, and especially strong, stiff members are needed.

Structural composite lumber products make productive use of wood materials that are fast growing or that might otherwise be treated as waste. They are dimensionally stable, up to three times as strong as conventional solid material, available in large sizes and long lengths, and consistent in quality.

Figure 3.30
An LVL beam, made of veneers similar to those used in the manufacture of plywood, resting on its side in preparation for installation on a concrete foundation wall. When placed in its final position, the beam will be rotated so that the laminations are oriented vertically in the beam. *(Photo by Joseph Iano.)*

Figure 3.31
A view of corner framing for a residential garage. The lower beam is made from PSL. A high-strength member such as this is needed to span the roughly 9-foot (2.7-m)-wide garage opening while supporting the floor load above. Above the top plates is an LSL rim board that encloses the floor framing behind it. This lower-strength member is adequate for this nonstructural function. *(Photo by Joseph Iano.)*

Wood I-Joists

Manufactured wood I-shaped members, called *I-joists*, are used for framing of both roofs and floors (Figure 3.32). The top and bottom flanges of the members may be made from solid lumber, laminated veneer lumber, or laminated strand lumber. The thinner webs, which connect the top and bottom flanges, may be plywood or OSB (oriented strand board; discussed later in this chapter). OSB is the most common choice because of its greater shear strength, an advantage in this application. These components use wood more efficiently than conventional dimension lumber, and they can span farther between supports. They are also lighter in weight than corresponding solid members, lack crooks and bows, are more dimensionally stable, and are available in lengths up to 40 feet (12 m). Because I-joists span farther than conventional framing lumber, floors framed with these components are sometimes more prone to uncomfortable vibration when subjected to normal occupant loads. Extra stiffening elements or oversized joists may be used to counteract this tendency.

Figure 3.32
A bundle of I-joists delivered to the construction site. The webs are made from OSB and the flanges from solid lumber. *(Photo by Joseph Iano.)*

Other Wood Products

Finger-Jointed Wood

Finger-jointed wood is made from short lengths of solid wood finger-jointed and glued into longer lengths. Compared to conventional sawn lumber, it is straighter, more stable, and more consistently free of defects. It also makes productive use of short-length scraps that might otherwise be treated as waste. *Structural finger-jointed lumber* is manufactured in dimension lumber sizes and can be used wherever conventional sawn members are used. Or, when rated Stud/Vertical Use Only, it can only be used in applications, such as studs, subject primarily to compressive stresses. Nonstructural *finger-jointed trim* is typically finished with paint, rather than a clear or translucent coating, to hide the joints and variation in appearance among the short lengths from which it is made.

Wood–Plastic Composites

Wood–plastic composite (*WPC*) products are made from blends of plastic with wood or agricultural fibers, usually in roughly equal proportions. Smaller quantities of ultraviolet stabilizers, pigments, lubricants, and biocides may be added. The mixture is heated and pressed, extruded, or injection-molded into final form. In comparison to their solid wood counterparts, WPC materials offer more consistent material quality, freedom from defects and distortion, and (depending on their formulation) sometimes superior resistance to moisture. They are used most often for exterior decking, exterior railing systems, and finish trim, both interior and exterior. Like structural composites, WPCs make productive use of rapidly renewable or waste materials. Some WPCs also have high recycled materials content.

Ingredients and processes used in the manufacture of *composite wood trim* vary widely, as do the workability, surface qualities, and durability of the finished products. In comparison to solid lumber, most wood–plastic composites expand and contract more with changes in temperature, so greater allowance for thermal movement must be made during installation. In the case of spanning members such as decking, the lesser stiffness of these materials necessitates closer spacing of the supporting members.

Bamboo

Bamboo is a rapidly growing woody grass. It is used in the manufacture of panel and plank alternatives to interior finish wood products, hardwood flooring, and exterior decking.

Plastic Lumber

Lumberlike products made entirely or mostly from plastic resins are called *plastic lumber*. When manufactured from recycled plastics, they may be called *recycled plastic lumber* (*RPL*). The use of plastic lumber reduces the demand for harvested wood and, where recycled ingredients are used, diverts solid waste from landfills.

In the manufacturing of plastic lumber, one or more resins may be used alone, or mixed with rubber, wood waste, glass fiber, or other materials, and then molded or extruded into solid or hollow shapes mimicking those of conventional solid lumber. In its finished state, plastic lumber is resistant to sun, water, and insects; does not require protective coatings or finishes; and is nontoxic, durable, and maintenance free, making it an especially attractive alternative to preservative-treated lumber for exterior applications. However, like WPCs, plastic lumber is more flexible than solid wood and must be supported at more closely spaced intervals. In addition, plastic lumber expands and contracts more with changes in temperature and so must be installed with greater allowances for thermal movement. The most common material used in the manufacture of plastic lumber, high-density polyethylene (HDPE), is obtained from the recycling of postconsumer waste, such as milk jugs and detergent bottles. Polystyrene and polyvinyl chloride are also used. Exterior decking, trim, fencing, and site furniture claim the largest share of the plastic lumber market in building construction.

Structural-grade plastic lumber (*SGPL*), most commonly made from HDPE reinforced with glass fibers, can be formulated to be at least as strong as conventional solid wood, though less stiff and more prone to long-term creep under permanent loads. SGPL planks, joists, beams, posts, piles, and other manufactured elements are used in the construction of decks, docks, piers, other types of exterior and marine structures, and even vehicular-capacity bridges.

Wood Panel Products

Wood in thin panel form is useful for many building applications (Figure 3.33). The panel dimensions are usually 4 × 8 feet (1220 × 2440 mm). Panels require less labor for installation than individual boards because fewer pieces must be handled, and wood panel products are fabricated in such a way that they minimize many of the limitations of boards and dimension lumber: Panels are more nearly equal in strength in their two principal directions than solid wood. Shrinking, swelling, checking, and splitting are greatly reduced. Additionally, panel products make more efficient use of forest resources than solid wood products through less wasteful ways of reducing logs to building products and through utilization (in some types of panels) of material that would otherwise be thrown away—branches, undersized trees, and mill wastes. Many wood panel products are made largely from recovered or recycled wood waste, and panels made from rapidly renewable vegetable fibers are also available.

Figure 3.33
Plywood is made of veneers selected to give the optimum combination of economy and performance for each application. This sheet of roof sheathing plywood is faced with a D veneer on the underside and a C veneer on the top side. These veneers, though unattractive, perform well structurally and are much less costly than the higher grades incorporated into plywood made for uses where appearance is important. *(Courtesy of APA—The Engineered Wood Association.)*

FIGURE 3.34
Three common wood panel products. From bottom to top: ¾-inch (19-mm) plywood, ½-inch (12-mm) OSB, and ¾-inch (19-mm) MDF. Particleboard, not shown, is visually distinguishable from fiberboard by its coarser, more varied particle composition.
(Photo by Joe Iano.)

Structural Panel Types

Structural wood panels include plywood, composite panels, and nonveneered panels (Figure 3.34). *Plywood* panels are made up of thin layers of wood veneer glued together. The grain on the front and back face veneers runs in the long direction of the sheet, whereas the grain in one or more interior crossbands runs perpendicular, in the shorter direction. There are always an odd number of layers in plywood, which equalizes the effects of moisture-related movement, but an interior layer may be made up of a single veneer or of two veneers with their grains running in the same direction. *Composite panels* have two parallel face veneers bonded to a core of reconstituted wood fibers. *Nonveneered panels* are made from various formulations of reconstituted wood fiber materials as follows:

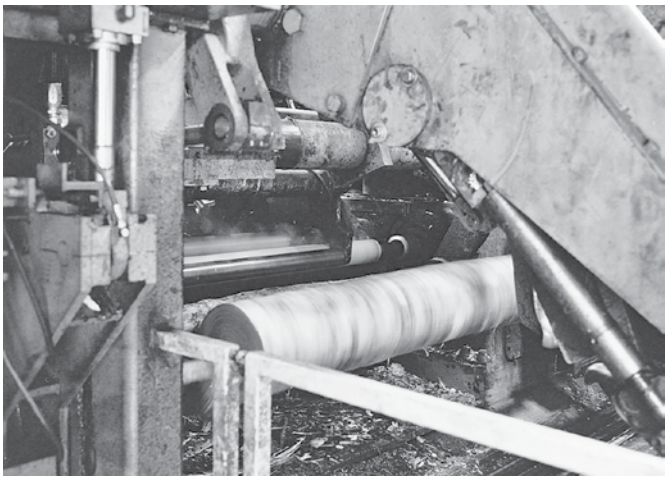
- *Oriented strand board* (*OSB*) is made of long shreds (strands) of wood compressed and glued into three to five layers. The strands are oriented in the same manner in each layer as the grains of the veneer layers in plywood. Because of the length and controlled orientation of the strands, OSB is the strongest and stiffest type of nonveneered panel. Because it can be produced from small trees and even branches, OSB is generally more economical than plywood. It is the material most commonly used for sheathing and subflooring of light frame wood buildings.
- *Particleboard* is manufactured in different density ranges and is made up of smaller wood particles than OSB that are compressed and bonded into panels. It is used mainly as a base material for wood veneer and plastic laminate. It is also used as an *underlayment panel* to create a very smooth base for the application of resilient flooring.
- *Fiberboard* is a very fine-grained board made of wood fibers and synthetic resin binders. It is generally limited to interior uses. The processing of the raw wood products in fiberboard manufacturing is more intensive than in the manufacture of particleboard, resulting in a panel that is dimensionally more stable, stiffer, better able to hold fasteners, and superior in its working and finishing characteristics. The most commonly used form of fiberboard is *medium-density fiberboard* (*MDF*). MDF is used in the production of cabinets, furniture, moldings, paneling, and many other manufactured products.

Standard structural panels are 4 × 8 feet (1220 × 2440 mm) in width and length and range in thickness from ¼ to 1 ⅛ inch (6.5 to 28.5 mm). Longer panels are manufactured for siding and industrial uses. The width and length of a structural panel is normally about ⅛ inch (3 mm) less than nominal, permitting panels to be installed with gaps between them to allow for moisture expansion. Panels intended for use as subflooring can be manufactured with tongue-and-groove edges that eliminate unevenness in the subfloor that could telegraph through the finish flooring.

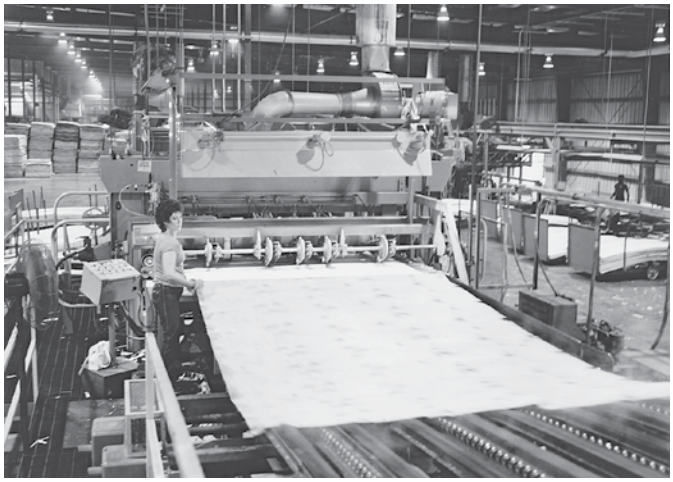
Plywood Production

Veneers for structural plywood panels are rotary sliced (Figure 3.35). The strip of veneer is clipped into sheets that pass through a drying kiln where, in a few minutes, their moisture content is reduced to roughly 5 percent. The sheets are then assembled into larger pieces, repaired as necessary with patches glued into the sheet to fill open defects, and graded and sorted according to quality (Figure 3.36). A machine spreads glue on the veneers as they are laid atop one another in the required sequence and orientations. The glued veneers are transformed into presses that apply elevated temperatures and pressures to create dense, flat panels. The panels are trimmed to size, sanded as required, graded, and gradestamped before shipping. Veneers of Grade B and higher are always sanded smooth, but panels intended for sheathing are left unsanded because sanding slightly reduces their thickness, which diminishes the strength of the panel. Panels intended for subfloors and floor underlayment are lightly *touch sanded* to produce a flatter, smoother surface.

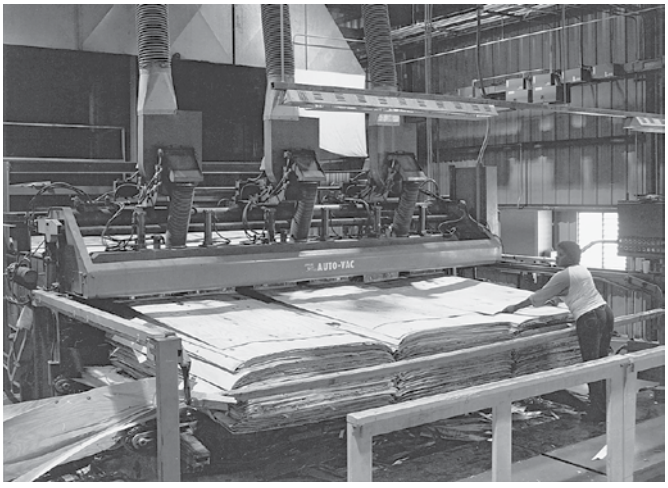
Where an especially smooth and durable surface is required, plywood may be finished with a resin-treated overlay to make a *medium-density overlay*



(*a*)

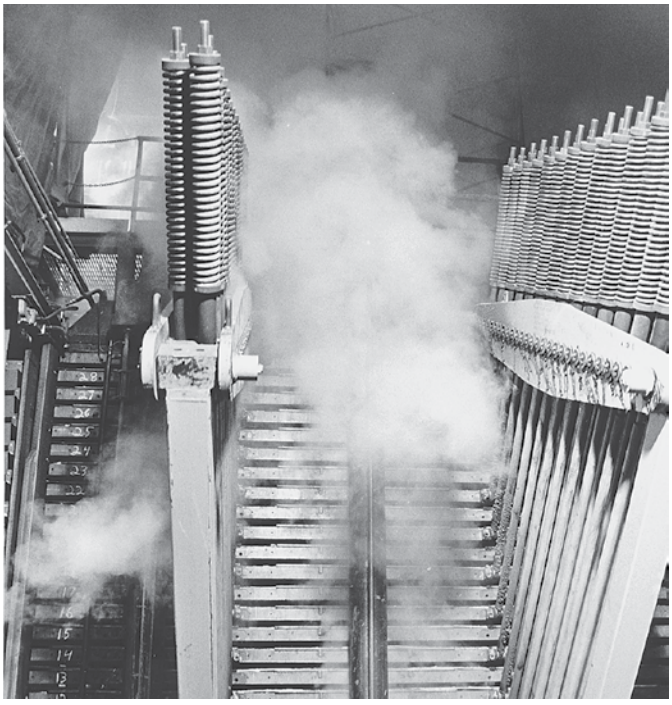


(*b*)



(*c*)

(*d*)



(*e*)

FIGURE 3.35

Steps in plywood manufacture. (*a*) A 250-horsepower lathe spins a softwood log as a knife peels off a continuous sheet of veneer for plywood manufacture. (*b*) An automatic clipper removes unusable areas of veneer and trims the rest into sheets of the proper size for plywood panels. (*c*) The clipped sheets are fed into a continuous forced-air dryer, along whose 150-foot (45-m) path they will lose about half their weight in moisture. (*d*) The higher grades of veneer are patched on this machine, which punches out defects and replaces them with tightly fitted wood plugs. (*e*) After veneers are graded, patched, sorted, layed up, and glued, they are squeezed individually between platens heated to 300°F (150°C) to cure the glue. This step is followed by trimming, sanding, or grooving as specified for each batch, and sorting finished plywood panels into bins, ready for shipment. *(Photos (b) and (e) courtesy of Georgia-Pacific; others courtesy of APA–The Engineered Wood Association.)*

TABLE 1

VENEER GRADES

A	Smooth, paintable. Not more than 18 neatly made repairs, boat, sled, or router type, and parallel to grain, permitted. Wood or synthetic repairs permitted. May be used for natural finish in less demanding applications.
B	Solid surface. Shims, sled or router repairs, and tight knots to 1 inch across grain permitted. Wood or synthetic repairs permitted. Some minor splits permitted.
C Plugged	Improved C veneer with splits limited to 1/8-inch width and knotholes or other open defects limited to 1/4 × 1/2 inch. Wood or synthetic repairs permitted. Admits some broken grain.
C	Tight knots to 1-1/2 inch. Knothole to 1 inch across grain and some to 1-1/2 inch if total width of knots and knotholes is within specified limits. Synthetic or wood repairs. Discoloration and sanding defects that do not impair strength permitted. Limited splits allowed. Stitching permitted.
D	Knots and knotholes to 2-1/2-inch width across grain and 1/2 inch larger within specified limits. Limited splits are permitted. Stitching permitted. Limited to Exposure 1 or Interior panels.

FIGURE 3.36

Softwood plywood veneer grades. Plywood with an A grade face offers the most attractive appearance. B grade allows more repairs in the veneer. Plywood with a C-plugged face is used for underlayment, where a smooth substrate is required to avoid telegraphing irregularities through thin finish flooring materials. Plywood for sheathing and subflooring is often referred to as "CDX," and consists of a C grade face and a D grade face, and is assembled with exterior glue. *(Courtesy of APA–The Engineered Wood Association.)*

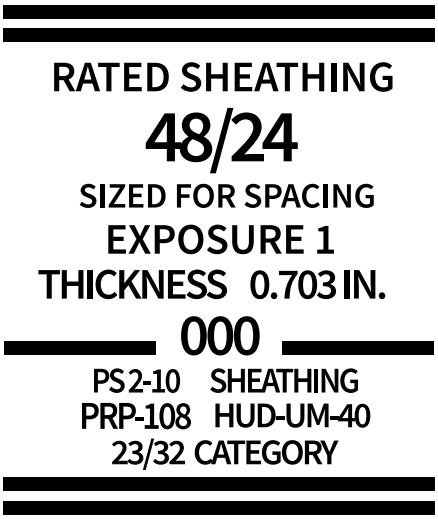


FIGURE 3.37

The 48/24 span rating on this structural panel gradestamp means that the panel can be used as roof sheathing over rafters or trusses spaced at 48 inches (1220 mm) or as subflooring over joists spaced at 24 inches (610 mm). The performance category is 23/32 with an actual thickness of 0.703 inches (19.9 mm). The Exposure 1 bond classification signifies that the panel is suitable for temporary exposure to the weather during construction, but not for permanent exterior exposure. Gradestamps are found on the back of each panel.

(*MDO*) or *high-density overlay* (*HDO*) panel. Overlaid panels are used in the construction of concrete forms, cabinetwork, furniture, exterior siding, signage, and other applications where durability and high surface-finish quality are required.

Composite panels and nonveneered panels are manufactured by analogous processes to the same set of standard sizes as plywood and to some larger sizes as well. Panels of all kinds used for sheathing and subflooring can also be manufactured with water-resistant coatings and edge sealers, and in the case of OSB, special resins, to provide better resistance to extended periods of wetting during construction.

Specifying Structural Panels

For structural uses such as subflooring and sheathing, wood panels are specified by thickness and/or *span rating*. The purpose of the span rating system is to permit the use of different types of panels while achieving the same structural objectives. For example, under normal loading conditions, any panel with a span rating of 32/16 may be used as roof sheathing over rafters spaced 32 inches (813 mm) or as subflooring over joists spaced 16 inches (406 mm). (The long dimension of the sheet must be placed perpendicular to the length of the supporting members.) Such a panel may be plywood, composite, or OSB, may be composed of any accepted wood species, and may be any of several thicknesses, so long as it passes the structural requirements for a 32/16 rating. The span rating is determined by laboratory load testing and is given on the gradestamp on the back of the panel, as shown in Figure 3.37.

When specifying panels by thickness, industry standards refer to nominal thickness, called *performance category*. Like the nominal sizes used to describe solid lumber, performance category is a conveniently expressed value, around which actual panel thickness may vary. Performance categories are expressed as nominal fractions of an inch, from ¼ to 1¼, but without any dimension. Depending on the thickness and type of panel, actual thickness may deviate between 1/64 and 1/16 inch (0.4 and 1.6 mm) from the performance category thickness.

I shall always remember how as a child I played on the wooden floor. The wide boards were warm and friendly, and in their texture I discovered a rich and enchanting world of veins and knots. I also remember the comfort and security experienced when falling asleep next to the round logs of an old timber wall; a wall which was not just a plain surface but had a plastic presence like everything alive. Thus sight, touch, and even smell were satisfied, which is as it should be when a child meets the world.

—Christian Norberg-Schulz, *Wooden Houses,* 1979

The designer must also select from two *bond classifications* for structural wood panels, either Exterior or Exposure 1. Panels marked Exterior are made with waterproof glues and the highest-quality veneers. They are the most durable panel type, suitable for use as exterior siding or in other applications permanently exposed to the weather. Exposure 1 panels are also made with waterproof glue but with veneers of a broader range of quality. They are commonly used for structural sheathing and subflooring, which will be protected from the weather once a building is finished, but must often endure long periods of wetting during construction. Exposure 1 panels are also used for interior applications. The complete performance specifications for structural wood panels are contained in the Voluntary Product Standards PS 1 and PS 2.

Other Panel Products

Hardboard is a thin, dense panel made of highly compressed wood fibers. It is available in various thicknesses and surface finishes, and in some formulations is durable against weather exposure. Hardboard is produced in configurations for residential siding as well as in general-purpose, non-structural panels of standard dimension.

Insulating fiberboard sheathing is a low-density panel, usually ½ or ¾ inch (13 or 19 mm) thick, made of wood or vegetable fibers and binders, and coated with asphalt for water resistance. It has some thermal insulating value and is used in wood construction chiefly as nonstructural wall sheathing, although some panels of this type are strong enough to also contribute modest lateral force resistance to a building frame. Other *cellulosic fiberboard* panels are made from finely processed recycled paper waste and are used for wall sheathing, acoustical isolation, carpet underlayment, and even structural roof decking. Panels of these types are low in cost, make productive use of waste or recycled materials, and help to conserve forest resources.

Hardwood plywood panels, made from birch, maple, poplar, or alder veneers, are popular for use in cabinetry and other finish carpentry. For higher-quality architectural woodwork, these panels may be faced with fine, hardwood face veneers.

Non-Wood Fiber Panels

Agrifiber or *biocomposite panels* are made from agricultural waste products, such as the stalks or chaff of wheat, rice, hemp, sorghum, and other crop residues that are otherwise usually disposed of as solid waste or by open-air burning.

Structural strawboard panels are made from wheat or rice straw. The straw is subjected to high pressure and temperature, causing the release of natural resins that bind the material into a solid mass roughly half as dense as wood. The compressed core is faced on both sides with OSB or other material to create a finished panel 2½ to 8 inches (64 to 200 mm) thick. These panels have significant structural capacity and can be used in place of conventional wood stud framing.

Nonstructural panels made from a variety of compressed agrifiber and binder mixtures are manufactured in thicknesses ranging from about ¼ inch to 1⅛ inches (6.5 to 30 mm). They can be used in place of MDF, particleboard, and interior plywood, for cabinetry and other interior woodworking applications.

Protecting Wood from Decay and Fire

Biological Threats to Wood

Once wood is harvested, it loses the natural protections of the living tree and becomes vulnerable to biological attack, or *biodeterioration*, principally by fungi and insects. *Fungi* are microscopic, threadlike plants that can cause mold and decay (rot) in wood. There are four necessary conditions for fungal growth:

1. Moisture
2. Oxygen
3. Suitable temperature range
4. A food source

For fungi to flourish, the wood moisture content must be at or above its fiber-saturation point, that is, roughly 30 percent. However, wood remains at least somewhat vulnerable to fungal attack any time its moisture content is above 20 percent, a condition readily encountered when wood is used in unprotected exterior exposures, or close to or in contact with the earth. Fungi need air to grow. The lack of available oxygen when wood is entirely submerged in water or buried in the earth below the water table accounts for the complete absence of decay in these environments. Optimal temperatures for fungal growth in wood are between 50°F and 95°F (10°C and 35°C). At lower temperatures, fungi become dormant, but can survive and resume growth when the temperature rises. At temperatures above 100°F (38°C), fungi begin to

die. Cellulose, lignin, and other components of the cell walls of wood provide suitable food for fungal growth.

Termites, carpenter ants, carpenter bees, and a variety of beetles are insects that use wood as source of food or for shelter. Wood submerged in brackish or salt waters is also vulnerable to a variety of marine-boring organisms.

Durable Construction Techniques

Most wood-attacking organisms need both air and moisture to live. Accordingly, most can be kept out of wood by constructing and maintaining a building so that its wood components are kept dry. This includes keeping wood well clear of the soil, ventilating unconditioned attics and crawlspaces to remove moisture, using good construction detailing to shed water and keep it out of building assemblies, using air and vapor retarders properly in conjunction with insulation to prevent the accumulation of condensation within exterior walls and roofs, and repairing roof and plumbing leaks as soon as they occur.

Preservative-Treated Wood

Preservative-treated wood (Figure 3.38) is impregnated with chemicals that are toxic to the biological organisms

FIGURE 3.38

Pressure preservative-treated lumber. Incising marks are visible on the board surfaces. The attached labels indicate the degree of preservative treatment, in this case sufficient for above-ground use. These boards are suitable, for example, for exterior decking or railings, or for use as foundation sill plates, but they are not appropriate for use in direct contact with soil. As part of the treatment process, this lumber has also been stained a light brown color to provide a more attractive appearance. *(Photo by Joseph Iano.)*

Chemical Wood Preservative Treatments

Creosote is an oily derivative of coal that is widely used to treat wood in engineering and marine structures. But the odor, toxicity, and unpaintability of creosote-treated wood make it unsuitable for most purposes in building construction. Pentachlorophenol is also an oil solution used to impregnate wood, and as with other oily preservatives, wood treated with it cannot be painted.

The most widely used wood preservatives in building construction are waterborne salts, which permit subsequent painting or staining. Many, such as alkaline copper quat (ACQ) and copper boron azole (CBA or CA), rely on high concentrations of copper for their preservative properties. The heavy concentrations of copper used in these preservatives also make the wood treated with them corrosive to many metals. For this reason, fasteners, framing hardware, and other metal components that come in contact with the wood must be made of metals not adversely affected, such as stainless steel, heavily galvanized (zinc-coated) steel, or copper alloy.

Chromated copper arsenate (CCA), a waterborne treatment containing chromium, copper, and arsenic, is no longer used as a preservative for wood in residential settings because of health concerns related to the leaching of arsenic from the treated wood.

Micronized copper (MC) preservatives also contain high concentrations of copper, but in the form of very small solid particles. Carbon-based PTI (propiconazole, tebuconazole, imidacloprid) preservatives are completely free of metals. Both of these are less corrosive to metals than the common waterborne salt treatments.

Borate compounds, such as sodium borate (SBX) and disodium octaborate tetrahydrate (DOT), are water-soluble treatments limited to above-ground applications protected from direct exposure to the weather. These compounds are not corrosive to metals and are often used in high-termite-risk areas, where all the structural lumber in a building may be treated.

that attack the wood. *Pressure* impregnation drives the preservative chemicals deep into the fibers of the wood, ensuring adequate protection. For some wood species, the surface of the wood is also punctured with an array of cuts in the surface, called *incising*, before the preservative is applied. Incising further improves the penetration of chemicals into the wood member, but at the cost of somewhat lowering the member's structural capacity.

Depending on the treatment chemical and wood species, drying of wood before treatment may be necessary. However, water-based treatments themselves significantly raise the moisture content of the treated wood. So most such wood is *kiln-dried after treatment* to restore it to a lower moisture content and lighter, more stable condition.

The concentration of preservative necessary to protect a given lumber product varies depending on the treatment chemical, the species of wood, and the severity of the environment in which the product will be used. To simplify the specification and selection of treated lumber, the American Wood Protection Association (AWPA) Use Category System provides designations corresponding to varying degrees of exposure (Figure 3.39). For example, wood deck posts, with ends in direct contact with the earth, should be treated to a higher Use Category (UC4A) than wood decking intended for use solely above ground (UC3B). It is then left to the treated wood producer to ensure that, for any particular use category, a suitable combination of wood species, chemical treatment, and treatment concentration is provided.

Other Treatments

Acetylated wood is exposed to the chemical acetic anhydride, causing changes in the cell walls of the wood that make the wood less absorptive of water and thereby resistant to insect attack and decay. This treatment also makes the wood more dimensionally stable, heavier, and stronger. *Thermally modified wood* is subjected to temperatures in the range of 400°F to 500°F (200°C to 260°C) in the absence of oxygen for several hours. This process also causes changes in the cell-wall structure of the wood, rendering it resistant to biological attack and more dimensionally stable but structurally weaker. *Glass infused wood* is made by introducing liquid sodium silicate under pressure into the wood, encasing the wood fibers in amorphous glass. This process increases the wood's strength and stability and reduces its combustibility as well. All these treatments have the added benefit of being free of potentially unhealthful chemicals.

Naturally Durable Woods

The heartwood of some species of wood is naturally resistant to decay and insects and can often be used where preservative-treated wood would otherwise be required. The International Building Code

Use Category	Service Conditions	Typical Building Uses
UC1	Interior construction, above ground, dry	Interior framing, woodwork, and furnishings where resistance to insect attack is required
UC2	Interior construction, above ground, damp	Interior construction where resistance to insect attack and/or moisture is required
UC3	Above-ground exterior	
UC3A	Not exposed to prolonged wetting, finish coated, readily sheds water	Exterior painted or stained siding, millwork, and trim
UC3B	Exposed to prolonged wetting, unfinished or poorly drained	Exterior decking, deck framing, railings, and uncoated trim
UC4	Ground contact	
UC4A	Normal exposure conditions, non-critical components	Fence, deck, and guardrail posts in relatively low decay risk areas
UC4B	High decay potential, critical or difficult-to-replace components	Permanent wood foundations, ground contact wood columns
UC4C	Extreme decay potential, critical components	Pilings, ground contact wood in severe decay areas

FIGURE 3.39

Part of the AWPA Use Category System, listing the categories most commonly specified for pressure preservative-treated wood used in building construction. The lumber in Figure 3.38, indicated as suitable for above-ground use, has been treated to meet the requirements of Use Category UC3B. *(Copyrighted material reproduced with permission from the American Wood Protection Association, www.awpa.com)*

recognizes black locust, black walnut, cedar, and redwood as decay-resistant species and Alaska yellow cedar, Eastern and Western red cedar, and redwood as termite-resistant species. Because the sapwood of these species is no more resistant to attack than the wood of any other tree, only heartwood should be used. A more comprehensive listing of wood species and their relative resistance to organic deterioration can be found in the USDA Forest Products Laboratory's *Wood Handbook*, listed in the references at the end of this chapter. Wood–plastic composites and plastic lumber, which are immune to decay or insect attack, are other alternatives to preservative-treated lumber.

Fire-Retardant Treatments

Fire-retardant treatments (*FRTs*) are accomplished by pressure impregnating wood with chemical salts that reduce wood combustibility. Fire-retardant-treated wood is expensive, and some such treatments are also mildly corrosive to metals. Fire-retardant-treated wood is permitted for use in some applications in noncombustible construction–type buildings. It is also used for exterior cladding and sheathing materials where structures are at risk of exposure to forest land wildfires. *Intumescent coatings* are heavy, paint-like coatings that expand when exposed to the high temperatures of fire, forming, for some period of time, a protective, insulating layer around the wood.

Wood Fasteners and Adhesives

Fasteners are often a structural weak link in wood construction. The interlocking timber connections of the past, laboriously mortised and pegged, were weaker than the members they connected because of the volume of wood removed to make the connection. Even with modern nails, screws, and bolts, it is usually impossible to insert enough of these fasteners in a connection to develop the full strength of the members being joined. And while adhesive joints and toothed-plate connections are capable of achieving the full strength of the connected members, they are largely limited to factory installation. As a result, the larger share of connections in wood structures depend primarily on direct bearing of one member on another for strength, while fasteners serve to hold members in position and keep the connection tight.

Nails

Nails are sharp-pointed metal pins that are driven into wood with a hammer or a mechanical gun. They are the favored means of fastening wood because they are inexpensive, require no predrilling of holes under most conditions, and can be installed rapidly. *Common nails* and the slightly slenderer *box* and *sinker nails* have flat heads and are used for structural fastening in light frame construction. Nails that are smaller in diameter and with smaller heads, such as *finish nails, casing nails*, and *brads*, are used to fasten finish woodwork, where they are less obtrusive than common nails (Figure 3.40).

In North America, the size of a nail is measured in *pennies* (abbreviated *d*; Figure 3.41). One explanation for this strange unit is that it originated long ago as the price of 100 nails of a given size. It persists today despite the loss of any such meaning. Box nails and finish nails are thinner in diameter but have the same length as common nails of equal penny size.

Sinkers and *coolers* are nails designed for easier driving into the wood. They combine features such as reduced diameter, shortened length, lubricant/adhesive coated shafts, and specially shaped heads. Joist hanger nails are the same diameter as the equivalent common nail, but much shorter (Figure 3.42). With the profusion of variations on the traditional common nail, it has become important

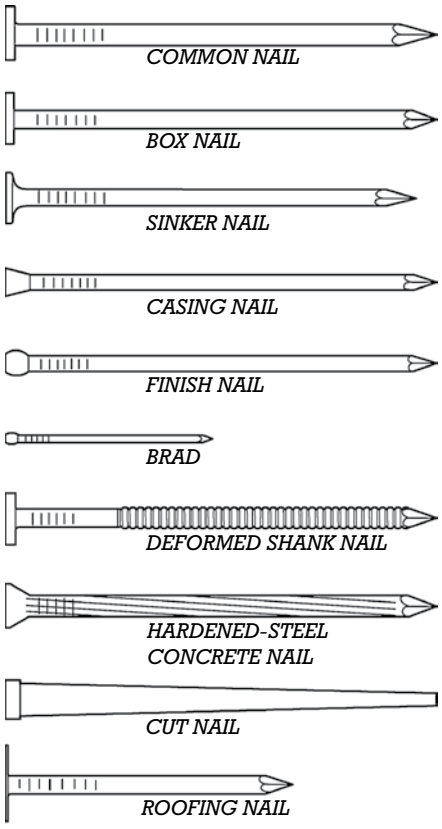


Figure 3.40

Most nailed framing connections are made with common nails, box nails, sinkers, or their machine-driven equivalents. Box nails are also used for fastening wood shingles and other types of siding. Casing nails, finish nails, and brads are used for attaching finish components. Their heads are set below the surface of the wood with a steel punch and the holes filled before painting. Deformed shank nails, which are more resistant to withdrawal from the wood than smooth shank nails, are used for attaching sheathing, subflooring, and floor underlayment, materials that might otherwise work loose in service. Hardened-steel concrete nails can be driven into masonry or concrete for attaching furring strips and sleepers. Cut nails, long ago used for framing connections, are still sometimes used for traditional wood flooring or cabinetry. Roofing nails have large heads to prevent tearing of soft asphalt shingles.

Size	Length	Shaft Diameter
2d	1" (25 mm)	0.072" (1.8 mm)
4d	1½" (38 mm)	0.099" (2.5 mm)
6d	2" (51 mm)	0.113" (2.9 mm)
8d	2½" (64 mm)	0.131" (3.3 mm)
10d	3" (76 mm)	0.148" (3.8 mm)
12d	3¼" (83 mm)	0.148" (3.8 mm)
16d	3½" (89 mm)	0.162" (4.1 mm)
60d	6" (152 mm)	0.262" (6.7 mm)

FIGURE 3.41
Common nail sizes, lengths, and shaft diameters. The abbreviation "d" stands for "penny." The four sizes most used in light frame construction, 16d, 10d, 8d, and 6d, are shown shaded.

FIGURE 3.42
***From left to right*: A 16d common nail, 16d box nail (note the more slender shaft but almost equal length), a coated 16d sinker (more slender and shorter than the common nail), an N10 joist hanger nail (hot-dip galvanized for greater corrosion resistance), and a short length of collated 10d nails for use in a nail gun. The left sides of the heads on the collated nails are slightly clipped to aid in firing reliability.**

to prevent confusion between fasteners of the same nominal size but differing in structural capacity. To avoid this problem, nails for use in structural connections may be specified by actual length and shaft diameter rather than conventional name and penny size.

The three methods of fastening with nails, *face nailing*, *end nailing*, and *toe nailing*, are shown in Figure 3.43. Each of these methods has its uses in building construction, as illustrated in Chapters 5 and 6.

Nails are ordinarily furnished *bright*, meaning that they are made of plain, uncoated steel. Nails that will be exposed to the weather should be corrosion-resistant, such as *hot-dip galvanized* (zinc-coated), aluminum, or stainless steel. This ensures the longevity of the fastener. Also, where nails remain exposed to view, such as when fastening exterior siding, trim, or decking, corrosion resistance prevents unsightly rust staining that can occur with bright nails. And as noted previously, corrosion-resistant nails are sometimes required when fastening wood members that have been chemically treated for resistance to decay or fire.

Machine-Driven Nails

Today, much nailing, both for framing and finish work, is done with powered *nail guns* rather than by hand. These guns use *collated nails* that are joined in linear arrays for swift loading into the magazine of the gun (Figure 3.42). Guns may be pneumatic, with air delivered via hose from a compressor, powered by internal combustion, with flammable gas stored in a cartridge within the gun, or electric-battery powered. When the nose of the nail gun is pressed against a solid surface and the trigger is pulled, a piston drives a nail with a single instantaneous blow. Various sizes of nail guns drive everything from 16d common nails to 2d finish nails, with significant productivity gains over hand nailing. With a nail gun, large nails can be driven home with a single trigger pull, sheathing fasteners can be set at a rate of one or more per second, and finish nails can be accurately and reliably set below the surface of the wood, ready for filling and painting.

Nail gun fasteners may mimic the size and shape of hand-driven nails, or they may have modified heads, or take the form of T-shaped pins or U-shaped *staples*. Modified-head fasteners fire more reliably with less frequent gun jams or bent nails. Less costly, lightweight staples are used to attach sheathing paper and thermal insulation. Heavier staples may be used for fastening cabinet components, wood flooring, shingles, underlayment panels, and even structural components. Wherever machine-driven nails or staples are used to join structural components, care must be taken to ensure that fasteners of the appropriate type and adequate load capacity are used.

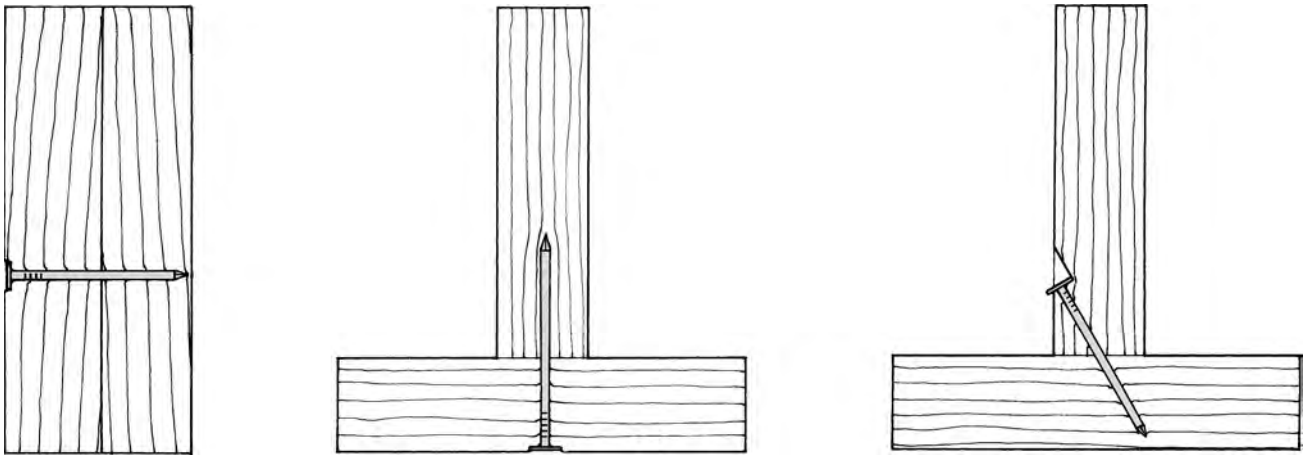


FIGURE 3.43
Face nailing is the strongest of the three methods of nailing. End nailing is relatively weak and is useful primarily for holding framing members in alignment until gravity forces and applied sheathing make a stronger connection. Toe nailing is used in situations where access for end nailing is not available. When properly installed, toe nails are surprisingly strong. Load tests show them to carry about 5/6 as much load as face nails of the same size.

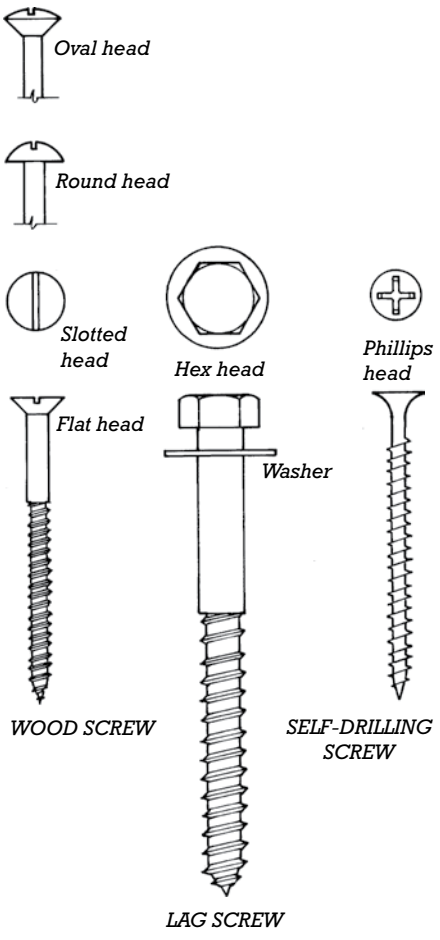
Screws

Screws are spiral-threaded fasteners installed by turning action whereby the threads draw the screw tightly into the material being fastened (Figure 3.44). In comparison to nails, screws cost more and take longer to install, but they can be inserted with greater precision, can exert greater clamping force between joined pieces, have greater holding power, and can be backed out and reinserted if a component has to be adjusted or remounted. Traditional *wood screws* require predrilled *pilot holes* into which the screw is inserted and then tightened with a screwdriver. Common uses include joining of cabinetry parts, installation of wide-plank flooring, mounting of hardware such as hinges, and other finish woodworking applications. Larger *lag screws* are used for heavier structural connections. They have square or hexagonal heads and are driven with a wrench rather than a screwdriver.

Screws may be made of steel, with or without a variety of metallic platings, such as black oxide, statuary bronze, yellow zinc, bright brass, clear zinc, and others. Where screws remain exposed, the finish plating is chosen based on appearance, and the desire for the fastener either to blend in or contrast with the materials being fastened. Some platings also offer modest corrosion resistance. However, where screws are used in exterior applications or corrosive environments, more corrosion-resistant metals (such as stainless steel, aluminum, or silicon bronze) are used.

Self-drilling wood screws do not require pilot holes and can be installed more quickly with power drivers. They are used for attaching subflooring to floor framing (rather than nailing, to reduce floor

FIGURE 3.44
Some common screw types. Flat-head screws are used without washers and are driven flush with the surface of the wood. Round-head screws are used with flat washers and oval-head screws with countersunk washers. Slotted-head and Phillips head screws, driven by flat-blade and Phillips drivers, respectively, are the most common. Self-drilling screws, such as the drywall screw shown here, do not require predrilled pilot holes.



squeaking), mounting gypsum wallboard to wall studs (to avoid nail popping), attaching exterior decking to deck framing (to resist loosening of deck boards caused by moisture-related expansion and contraction), and wherever else the precision and holding power of screws are benefits. Like nails, some self-drilling screw types are available in collated strips for use in self-feeding power guns.

Screws seem to come in a never-ending variety of types (Figure 3.45). Special driver shapes, such as square or star-shaped, engage and hold screws more reliably and can transmit greater torque than slotted or Phillips drivers. Wider, steeper thread patterns improve holding strength and allow for faster driving. Contoured heads recess neatly below the surface of the wood. Multipitch thread patterns improve a screw's ability to draw fastened pieces tightly together. Steel screws with organic coatings can be matched to the finish color of the fastened material and provide corrosion resistance at less cost than fasteners made of stainless steel. Slender, small-headed screws can be installed almost as unobtrusively as finish nails. In structural applications, longer, larger-diameter self-drilling screws can be installed more quickly and easily than conventional lag screws or bolts.

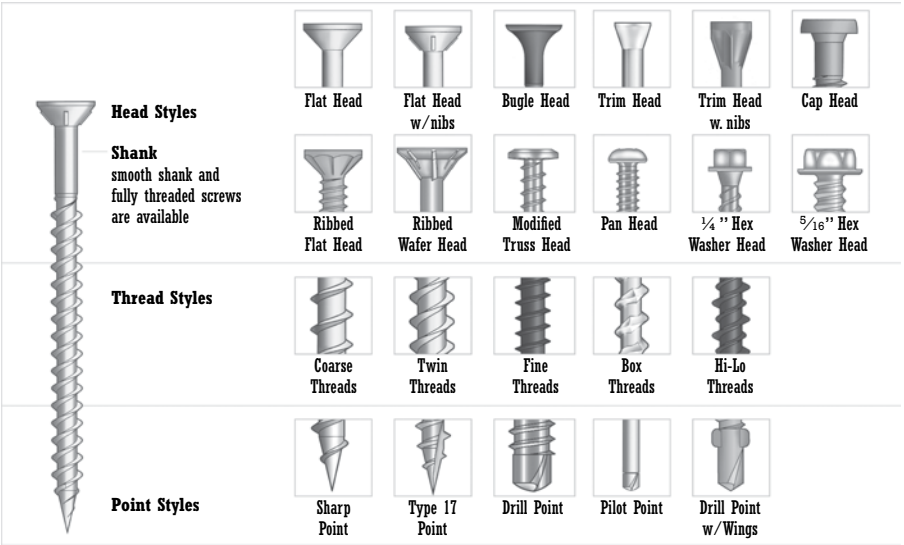


FIGURE 3.45

A manufacturer's chart illustrating variations in styles of power-driven screw heads, shanks, threads, and points. *(Courtesy of Simpson Strong-Tie Company Inc.)*

Bolts

Bolts are used mainly for structural connections in heavy timber framing and in wood light framing for fastening ledgers, beams, or other heavy applications. They are installed into predrilled holes. A wrench is used to turn the *nut*, opposite the bolt head, thereby tightening the bolt in place. Flat steel disks called *washers*, inserted under the head and nut, distribute the clamping force from the bolt across a greater area of wood and reduce crushing of the wood fibers. Commonly used sizes range in diameter from ⅜ to 1 inch (9.5 to 25 mm) in almost any desired length (Figure 3.46).

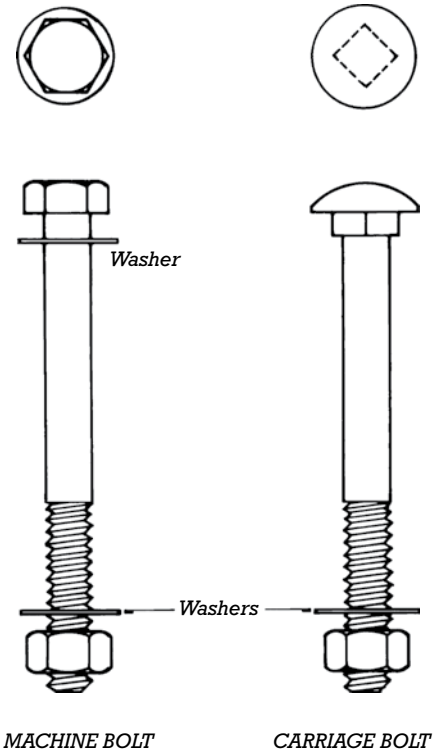


FIGURE 3.46

Both machine bolts and carriage bolts are used in wood construction. Carriage bolts have a broad button head that needs no washer and a square shoulder under the head that is forced into the drilled hole in the wood to prevent the bolt from turning as the nut on the opposite end is tightened.

Timber Connectors

Various types of specially designed connectors can provide increased load-carrying capacity over bolted, screwed, or nailed connections, particularly when fastening larger-dimension wood members. The *split-ring connector* (Figure 3.47) is inserted in matching circular grooves to mate pieces of wood clamped together with a central bolt. This connector provides greater capacity by spreading the load across a larger area of wood than can be done with one or a few bolts. The split permits the ring to adjust to wood shrinkage.

Timber rivet connections are formed by fastening steel plates to large wood members with spike-like fasteners. Unlike nails, timber rivets are oval in cross section and driven so that the wider axis of the rivet is always parallel to the grain of the timber. By driving arrays of rivets in closely spaced but carefully controlled patterns, an area of wood becomes compacted and prestressed, creating a connection between the riveted plate and the wood that is stronger than possible with ordinary nails and less labor intensive than a bolted or split-ring connection. Additional examples of connectors for Heavy Timber construction are illustrated in Chapter 4.

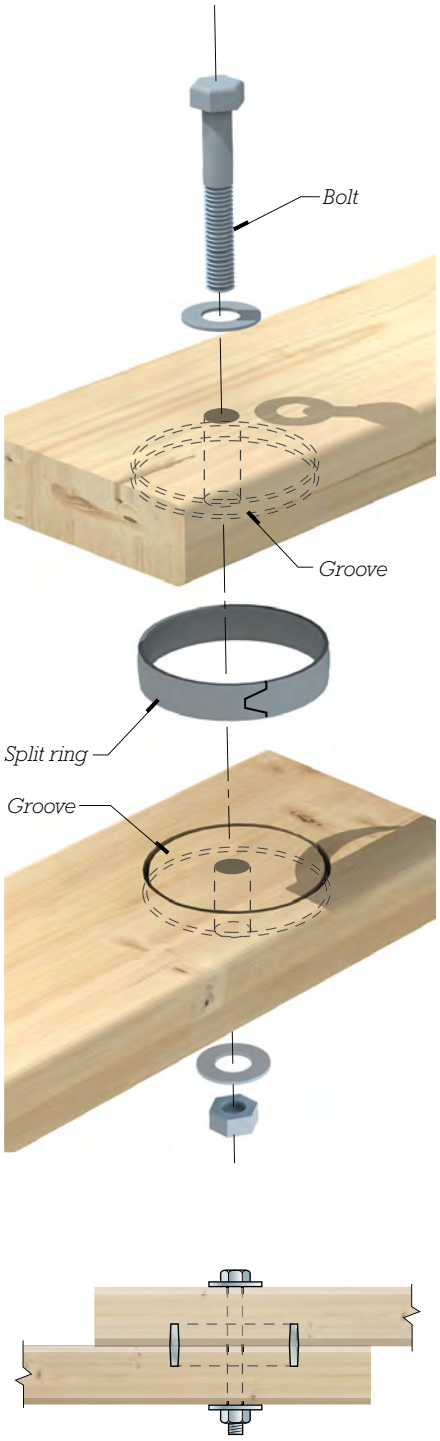


FIGURE 3.47
Split rings are high-capacity connectors used in heavily loaded joints of timber frames and trusses. After the center hole has been drilled through the two pieces, they are separated and the matching grooves are cut with a special rotary cutter driven by a large power drill. The joint is then reassembled with the ring in place.

Toothed Plates

Sheet metal *toothed plates* (Figure 3.48), similar to timber rivet connections but lighter, are used in factory-produced lightweight roof and floor trusses (Figure 3.51). They are driven into the wood with hydraulic presses, pneumatic presses, or mechanical rollers and act as splice plates, each with a very large number of built-in nail-like points. They are effective and economical connectors: No drilling or gluing is required, they can be installed rapidly, and their multiple closely spaced points interlock tightly with the fibers of the wood.

Metal Framing Devices

Dozens of ingenious sheet metal and metal plate devices are manufactured for joining wood members or strengthening their joints. The most frequently used is the *joist hanger*, but all of the devices shown in Figures 3.49 and 3.50 find extensive use. There are two parallel series of this type of device, one made of sheet metal for use in light framing and one made of thicker metal plate for heavy timber framing. The devices for light framing are attached with nails and the heavier devices with bolts or large screws. Where such devices will be exposed to the weather or to lumber treated with corrosive chemical treatments, they should be made from corrosion-resistant galvanized steel or stainless steel. To prevent galvanic corrosion between dissimilar metals, fasteners for metal framing devices should match the framing device material. That is, galvanized steel framing devices should be fastened with galvanized steel fasteners, and stainless steel devices should be fastened with stainless steel fasteners.

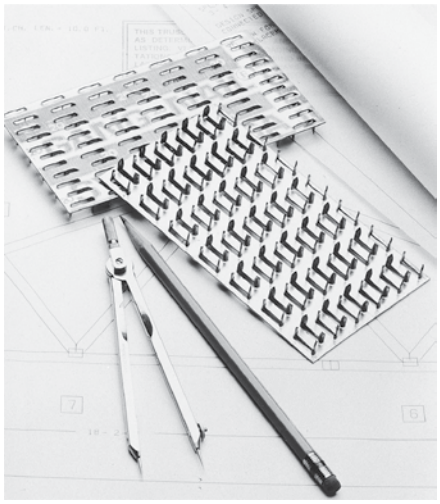


FIGURE 3.48
Manufacturers of toothed-plate connectors also manufacture the machinery to install them and provide computer programs to aid truss fabricators in designing and detailing trusses for specific buildings. *(Courtesy of Gang-Nail Systems, Inc.)*

Wood Adhesives

Structural wood adhesives form bonds that are at least as strong, stiff, and durable as the members they connect. Adhesives rated for full exterior exposure are capable of repeated, long-term soaking and drying without degradation of the wood bond. Others, rated for limited exterior or interior exposures, are less water resistant, and their use is restricted to applications correspondingly less exposed to wetting. Structural adhesives are also tested for heat resistance, to protect against premature delamination of the manufactured products during a building fire.

Alternatives to Synthetic Polymer Adhesives

Since the middle of the 20th century, adhesives used in wood product manufacturing have been derived mostly from petroleum and natural gas. These synthetic polymers are consistent in formulation and performance, high in strength and stiffness, and (where needed) capable of providing excellent water resistance. More recently, efforts to reduce reliance on nonrenewable resources and concern for the human health effects of some

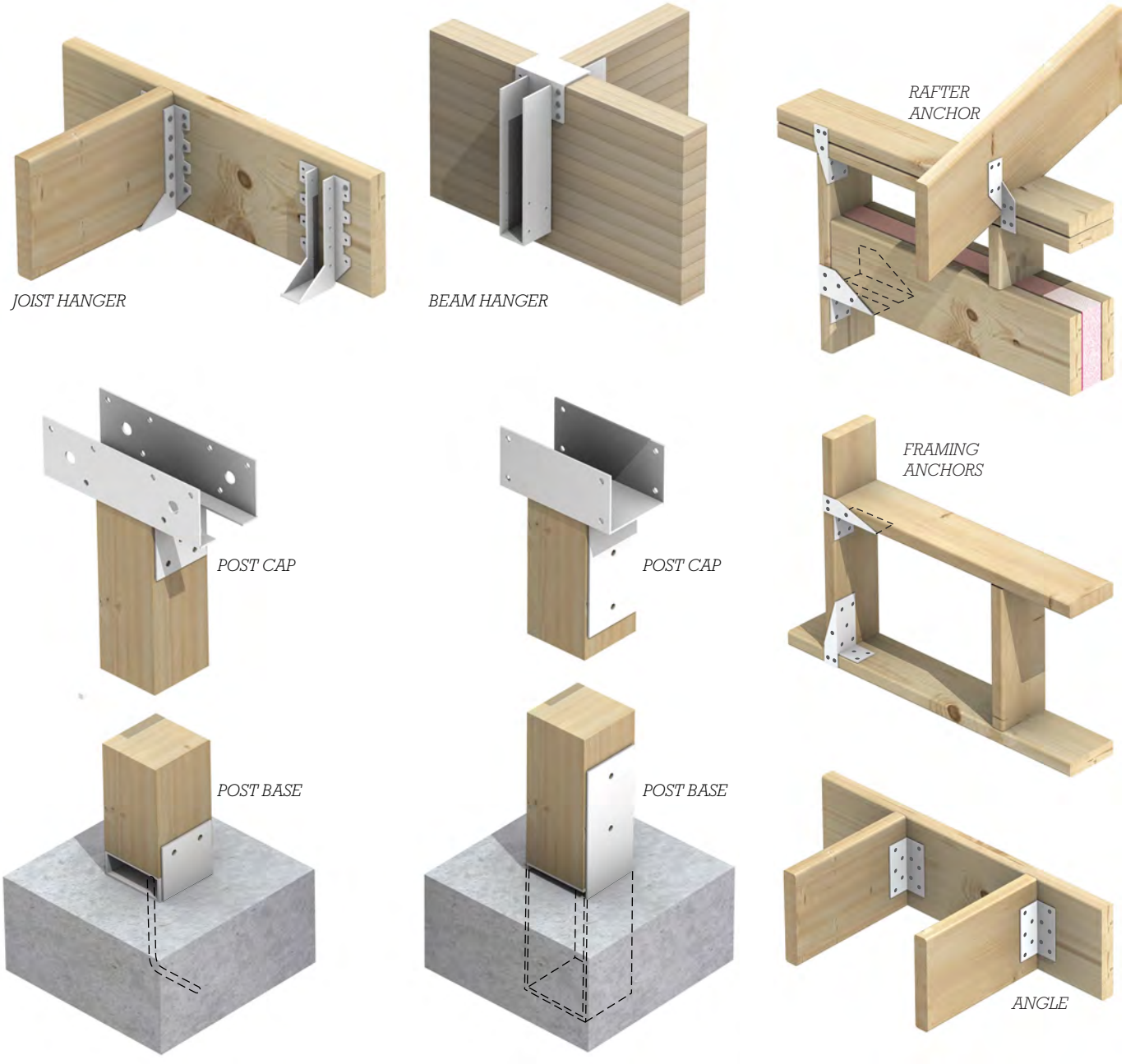


Figure 3.49
Joist hangers are used to make strong connections in floor framing wherever wood floor and roof framing members bear on one another at right angles. They are attached with special short nails driven through the holes punched in the hangers. Heavier steel plate hangers are used primarily in Heavy Timber construction. Post bases serve the twofold function of preventing water from entering the end of the post and anchoring the post to the foundation. The bolts and lag screws used to connect the wood members to the heavier connectors are omitted from this illustration.

Figure 3.50
The sheet metal connectors shown in this diagram are less commonly used than those in Figure 3.49 but are invaluable in solving special framing problems and in reinforcing frames against wind uplift and earthquake forces.

synthetic adhesives (see sidebar) have led to renewed interest in *bio-based adhesives* derived from agricultural and animal byproducts. Soy protein–based structural adhesives, suitable for exterior exposure, have gained a significant foothold in wood product manufacturing. Adhesives derived from tannin and lignin (wood and paper manufacturing byproducts), and various animal proteins, are also gaining renewed attention.

Wood Product Adhesives and Formaldehyde

Formaldehyde is an organic compound with many natural sources, including, in small amounts, wood itself. It is an ingredient in some adhesives and binders used in the manufacture of wood products. It is also a recognized carcinogen that, in higher concentrations, can cause a range of adverse health effects in humans.

Phenol-formaldehyde (*PF*) is a structural adhesive, rated for full exterior exposure, used in the production of panels rated Exterior and Exposure 1 and in other wood products. Formaldehyde gas emissions from PF after manufacture are very low, below the exposure limits established by prevailing air quality and health standards. Though rated for exterior exposure, panels manufactured with PF may be also selected for interior use because of their low emissions. Phenol resorcinol formaldehyde (PRF) has similar properties to PF, but with faster cure times.

Urea-formaldehyde (*UF*) is a structural wood adhesive with less moisture resistance, rated for interior (dry) exposure only. Due to lower manufacturing costs and other advantages associated with its use, UF resin has historically been a popular choice in the manufacture of interior plywood, MDF, particleboard, doors, engineered wood flooring, and other products. However, UF, unlike PF, continues to emit formaldehyde gas long after manufacturing is complete and the products have been put into service. Because these products are destined almost exclusively for the building interior, their emissions can adversely affect indoor air quality and occupant health. A third resin type, melamine-formaldehyde, or MF, has emissions levels that fall in between UF and PF.

Other adhesives and resins are made without formaldehyde and can substitute for UF, PF, and other formaldehyde-containing adhesives in many applications. Described as *no added formaldehyde* (*NAF*), examples include polyvinyl acetate, isocyanurates such as polymeric MDI, urethanes, and various bio-based formulations.

Since the 1980s, formaldehyde gas emissions from manufactured wood products have come under increased scrutiny, and federal and state standards for safe emission levels have become more stringent. At this time, these standards are applied mainly to particleboard, fiberboard, and hardwood plywood: products intended for interior use that have, in the past, relied on UF adhesives. Most structural products, such as structural plywood and OSB, glulams, CLTs, and structural composite products, are exempted from these regulations because of their reliance on PF and other adhesives that have been demonstrated to be very low-emitting.

Wood Adhesives on the Construction Site

Wood adhesives are used less on the construction site, where it is more difficult to clamp and hold glued joints and to maintain controlled temperature and humidity until the adhesive has cured. In rough carpentry work, subflooring panels are frequently adhered to their supporting wood framing, with the adhesive being applied with a sealant gun. The nails or screws used to fasten the panels serve as the primary structural connection and also clamp the adhesive joint.

Finish carpenters use adhesives, usually in combination with nails or screws, to improve the strength and stability of joints in finish trim, wood flooring installations, and other site-built woodwork. (See, for example, Figure 7.26.) In the woodworker's fabrication shop, adhesives are used in the veneering of wood paneling and the fabrication of cabinets and furniture.

Prefabricated Wood Components

Wood products of all types can be used in the manufacture of *prefabricated wood components*. Factory fabrication eliminates weather-related delays and produces components that are structurally efficient, precise in dimension, and consistent in quality. On the construction site, prefabricated components can be erected faster, with smaller work crews and less waste.

Trusses

Trusses for both roof and floor construction are manufactured in small, highly efficient plants in every part of North America. Most are based on 2 × 4s and 2 × 6s joined with toothed-plate connectors. The designer or builder need only specify the span, roof pitch, and desired overhang detail. The truss manufacturer then uses a preengineered design for the specified truss or custom engineers a truss design and develops the necessary cutting patterns for its constituent parts. The manufacture and transportation of trusses are shown in Figure 3.51, and several uses of trusses are depicted in Chapter 5.

Roof trusses use less wood than a comparable frame of conventional rafters and ceiling joists. Like floor trusses, they span the entire width of the building in most applications, allowing the designer greater freedom to locate interior partitions anywhere they are needed. The chief disadvantages of roof trusses as they are most commonly used are that they make the attic space unusable and generally restrict the designer to the spatial monotony of a flat ceiling throughout the building.

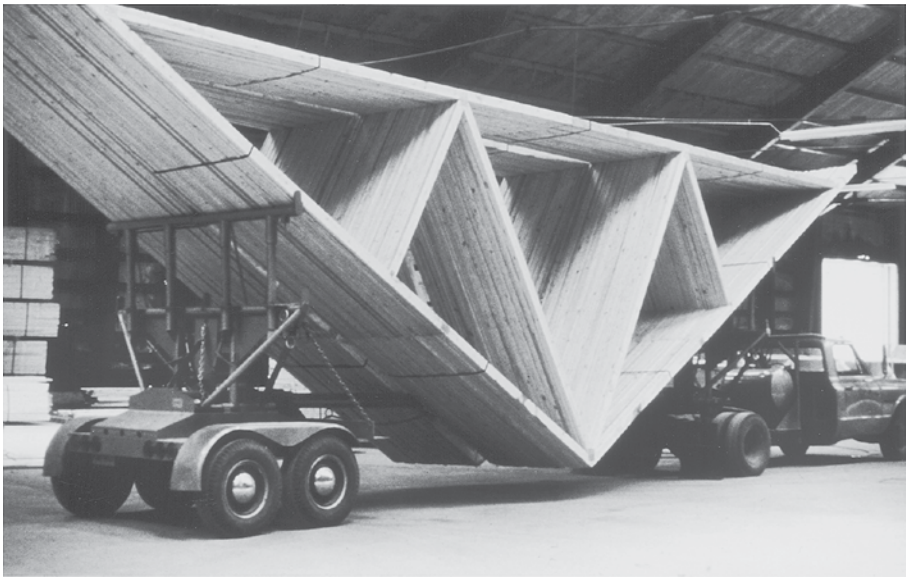


FIGURE 3.51

Manufacturing and transportation of wood trusses. (*Top*) Factory workers align the wood members of a roof truss and position toothed-plate connectors over the joints, tapping them with a hammer to embed them slightly and keep them in place. The roller marked "Gantry" then passes rapidly over the assembly table and presses the plates firmly into the wood. (*Middle*) The trusses are transported to the construction site on a special trailer. (*Bottom*) Trusses can be designed and produced in almost any configuration. *(Photos courtesy of the Wood Truss Council of America.)*

Prefabricated Panels

Framed panels are simple sections of conventional dimension lumber framing, sheathed with plywood or OSB, trucked to the construction site, and assembled into a complete building frame. Wall, floor, and roof panels with greater structural capacity are made with sheets of plywood or OSB applied to both panel faces. In *structural insulated panels* (*SIPs*), the panels are adhered to a stiff plastic foam core. In *stressed-skin panels* (*SSPs*), the panels are attached to dimension lumber framing. SIPs (pronounced "sips"), in particular, are a popular choice for the construction of highly energy-efficient homes and small buildings (Figure 3.52).

In *panelized construction*, whole sections of walls or floors are conventionally framed and sheathed in the factory, then trucked to the construction site and installed in rapid succession. Although prefabrication of more complex assemblies—including, for example, insulation, wiring, windows, doors, and exterior and interior finishes—is technically feasible, it is less frequently done due to the added complexities of joining up all such systems in the field and obtaining the needed building code inspections in the factory setting.

Factory-Built Housing

Houses may be built entirely in a factory, at times even complete with furnishings, and then transported to prepared foundations, where they are set in place and made ready for occupancy in a matter of hours or days. A *manufactured home* (referred to in the past as a *mobile home*) is built on its own permanent, towable chassis and is designed to comply with a federal code administered by the U.S. Department of Housing and Urban Development. A factory-built *modular home* is designed to comply with the building code in effect where the home will be

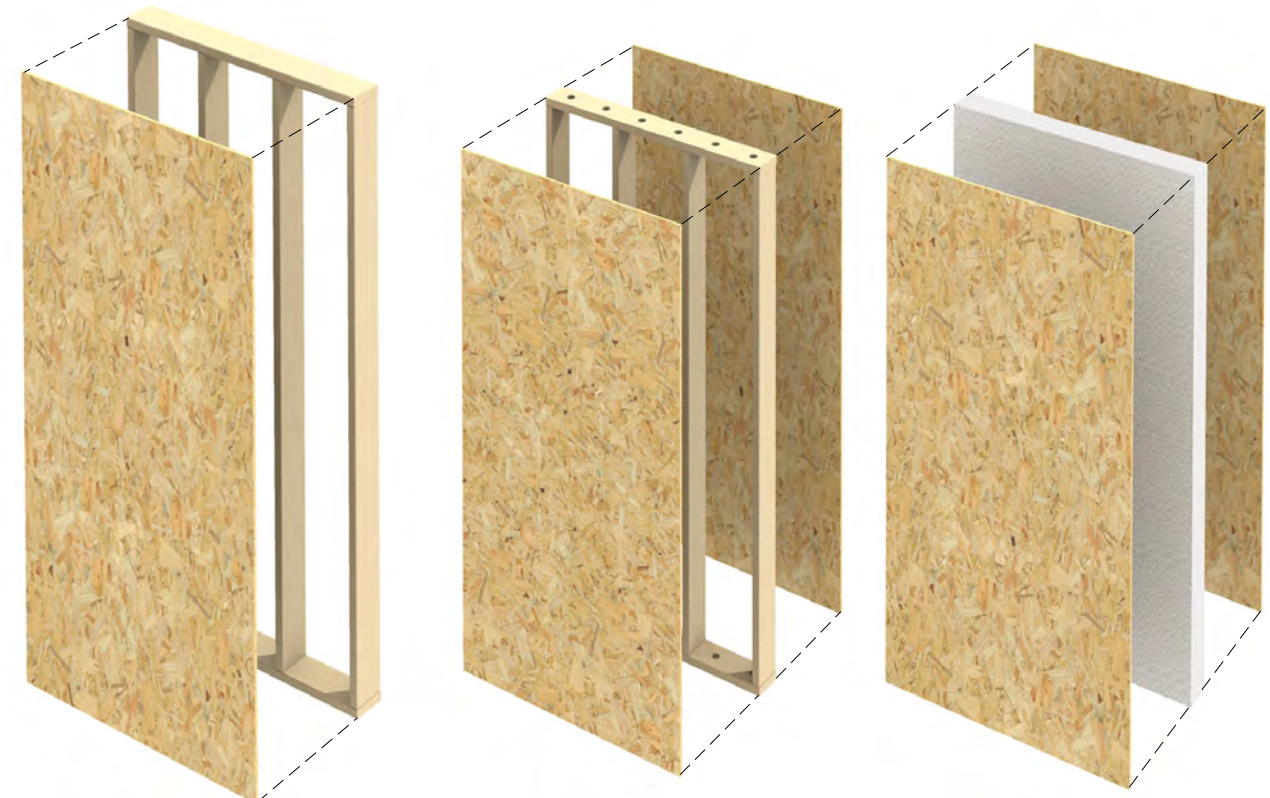


FIGURE 3.52

Three types of prefabricated wood panels. The framed panel is identical to a segment of a conventionally framed wall, floor, or roof. The facings on the stressed-skin panel are bonded by adhesive to wood framing members to form a structural unit in which the facings carry the major stresses. A structural insulated panel, also called a *sandwich panel*, functions structurally in the same way as a stressed-skin panel, but its facings are bonded to a core of insulating foam.

located and is transported on a conventional flat-bed tractor-trailer. Both manufactured and modular homes are constructed in units not wider than 14 to 16 feet (4.27 to 4.88 m) to permit transport on public roads. Multiple units may be combined side by side or stacked vertically to make the complete structure.

At their least expensive, manufactured homes are sold at a fraction of the price of conventionally constructed homes of the same floor area. This is due in part to the economies of factory production and mass marketing and in part to the use of components that are lighter and less costly, and therefore shorter in life expectancy. However, both manufactured and modular homes may also be constructed to levels of cost and quality equal to those conventionally constructed, but with the potential to significantly reduce the duration of construction on site.

MasterFormat Sections for Wood, Plastics, and Composites

06 05 00	**COMMON WORK RESULTS FOR WOOD, PLASTICS, AND COMPOSITES**
06 05 73	Wood Treatment
06 11 00	**WOOD FRAMING**
06 11 13	Engineered Wood Products
06 12 00	**STRUCTURAL PANELS**
06 12 16	Stressed-Skin Panels
06 16 00	**SHEATHING**
06 16 23	Subflooring
06 16 26	Underlayment
06 16 36	Wood Panel Product Sheathing
06 17 00	**SHOP-FABRICATED WOOD**
06 17 13	Laminated Veneer Lumber
06 17 19	Cross-Laminated Timber
06 17 23	Parallel Strand Lumber
06 17 33	Wood I-Joists
06 17 53	Shop-Fabricated Wood Trusses
06 18 00	**GLUE-LAMINATED CONSTRUCTION**
06 51 00	**STRUCTURAL PLASTIC SHAPES AND PLATES**
06 53 00	**PLASTIC DECKING**
06 65 00	**PLASTIC TRIM**
06 82 00	**COMPOSITE TRIM**

Key Terms

bark
cambium
sapwood
heartwood
pith
cellulose
lignin
grain
springwood, earlywood
summerwood, latewood
softwood
hardwood
tracheid
ray
fiber
vessel, pore
grain figure
environmentally certified wood
Forest Stewardship Council (FSC)
sequestered carbon
reclaimed lumber
ultra-low-emitting formaldehyde (ULEF) resins
lumber
roundwood
plainsawn, flat-grain
quartersawn, vertical-grain
fleck, flake
riftsawn
moisture content (MC)
free water
bound water
fiber saturation point
equilibrium moisture content (EMC)
seasoning
kiln drying
air drying
green lumber
sticker
longitudinal shrinkage
radial shrinkage
tangential shrinkage
check
surfaced
wood plane
surfaced four sides (S4S)
surfaced two sides (S2S)
unsurfaced
S-DRY
S-GRN
growth characteristics
manufacturing characteristics
knot
knothole
decay
insect damage
split
check
crook
bow
twist
cup
wane
structural grading
visual grading
machine grading
machine stress rated (MSR) lumber
machine evaluated lumber (MEL)
E-rated lumber
species group, species combination
appearance grading
nominal size
actual size
board
dimension lumber
timber
board foot
veneer
rotary-cut veneer, rotary-sliced veneer
lathe
plainsliced veneer
quartersliced veneer
riftsliced veneer
sliced veneer
sawn veneer
flitch
sequenced veneer
glue-laminated wood (GLT), glulam
finger jointed
scarf jointed

hybrid glulam beam
FRP reinforced glulam
cross-laminated timber (CLT)
mass plywood panel
nail-laminated timber (NLT), mechanically laminated timber
dowel-laminated timber (DLT)
structural composite lumber, engineered lumber
laminated strand lumber (LSL)
oriented strand lumber (OSL)
laminated veneer lumber (LVL)
parallel strand lumber (PSL)
I-joist
structural finger-jointed lumber
finger-jointed wood trim
wood–plastic composite (WPC)
composite wood trim
bamboo
plastic lumber
recycled plastic lumber (RPL)
structural-grade plastic lumber (SGPL)
structural wood panel
plywood
composite panel
nonveneered panel
oriented strand board (OSB)
particleboard
underlayment panel
fiberboard
medium-density fiberboard (MDF)
touch sanded
medium-density overlay (MDO)
high-density overlay (HDO)
span rating
performance category
bond classification
hardboard
insulating fiberboard sheathing
cellulosic fiberboard
hardwood plywood
agrifiber panel, biocomposite panel
biodeterioration
fungi
preservative-treated wood
pressure-treated wood
incising
kiln-dried after treatment
acetylated wood
thermally modified wood
glass infused wood
fire-retardant treatment (FRT)
intumescent coating
nail
common nail
box nail
sinker nail
finish nail
casing nail
brad
penny (d)
cooler
face nailing
end nailing
toe nailing
bright nail
hot-dip galvanized nail
nail gun
collated nail
staple
screw
wood screw
pilot hole
lag screw
self-drilling wood screw
bolt
nut
washer
split-ring connector
timber rivet connection
toothed plate
joist hanger
structural wood adhesive
bio-based adhesive
formaldehyde
phenol-formaldehyde (PF)
urea-formaldehyde (UF)
no added formaldehyde (NAF)
prefabricated wood components
truss
framed panel
structural insulated panel (SIP), sandwich panel
stressed-skin panel (SSP)
panelized construction
manufactured home, mobile home
modular home

Review Questions

1. In a tree, what are springwood and summerwood cells? How do they differ?

2. Name three softwood species and three hardwood species. What is one common use for softwood lumber? What is one for hardwood lumber?

3. What are the differences between plainsawn and quartersawn lumber? What applications are appropriate for each?

4. Discuss the changes in moisture content and the effects of these changes on a piece of dimension lumber from the time the tree is cut, through its processing, and until it has been in service in a building for an entire year.

5. A sample 8-foot-long 2 × 4 weighs 10 pounds. After drying in an oven, it weighs 8 pounds. What was its moisture content before drying? In its original condition, was it adequately seasoned for use as a structural framing member?

6. Give three examples of growth characteristics and three examples of manufacturing characteristics.

7. Give an example of a structural grade wood species group. Why are species groups used in structural grading?

8. Give the actual cross-sectional dimensions of the following pieces of kiln-dried lumber: 1 × 4, 2 × 4, 2 × 6, 2 × 8, 4 × 4, 4 × 12.

9. What method of slicing is used for structural plywood panels? What is a common method for hardwood veneers destined for fine architectural woodwork?

10. What are the advantages of using structural composite lumber rather than solid lumber?

11. Give three advantages of wood–plastic composites in comparison to solid lumber. What are two common uses for wood–plastic composites?

12. What are three common structural panel products? What is the most commonly available panel size (length and width)?

13. Name the most appropriate plywood veneer grade for each of the following applications: (a) the outer face of a wall or roof sheathing panel, (b) underlayment to receive a thin, resilient vinyl floor covering, (c) plywood to receive a paint finish in an application demanding the highest possible finish quality.

14. What is meant by a structural panel span rating of 32/16? What types of wood products are rated this way?

15. Give one example of an agrifiber panel. What is one reason to select an agrifiber panel rather than one manufactured from wood products?

16. For what reasons might you specify preservative-treated wood?

17. Name three wood species that have naturally decay- or insect-resistant heartwood.

18. Why are nails the most common fastener type used in wood construction?

19. Which is longer, a common nail or a joist hanger nail, both made from the same diameter wire?

20. When are screws preferable to nails for fastening wood?

21. List two possible advantages of a bio-based adhesive over a synthetic polymer adhesive.

Exercises

1. Visit a nearby lumberyard or building materials supply center. Examine and list the species, grades, and sizes of lumber carried in stock. For what uses are each of these intended? While at the yard, look also at the available range of fasteners.

2. Pick up a number of scraps of dimension lumber from a shop or construction site. Examine each to see where it was located in the log before sawing. Note any drying distortions in each piece: How well do these correspond to the distortions you would have predicted? Measure the width and thickness of each scrap and compare your measurements to the specified actual dimensions for each.

3. Assemble samples of as many different species of wood as you can find. Learn how to tell the different species apart by color, odor, grain figure, ray structure, relative hardness, and so on. What are the most common uses for each species?

4. Visit a construction site and list the various types of lumber and wood products being used. Look for a gradestamp on each and determine why the given grade is being used for each use. If possible, look at the architect's written specifications for the project and see how the lumber and wood products were specified.

Selected References

APA–The Engineered Wood Association. *Engineered Wood Construction Guide*. Tacoma, WA, revised periodically.

This 92-page guide to engineered wood products (such as plywood, OSB, glulam, CLT, structural composite lumber, and I-joists) and their uses is available as a free download from the association's website, www.apa.org.

Hoadley, R. Bruce. *Understanding Wood: A Craftsman's Guide to Wood Technology* (2nd ed.). Newtown, CT, Taunton Press, 2000.

Vividly explains the properties of wood as a material of construction.

USDA Forest Products Laboratory. *Wood Handbook: Wood as an Engineering Material*. Madison, WI, 2010.

Provides comprehensive coverage of wood properties and the use of wood in construction. This reference has been in print publication since the 1930s. It can also be downloaded free from the Forest Product Laboratory's website, www.fpl.fs.fed.us.

Western Wood Products Association. *Western Lumber Product Use Manual*. Portland, OR, updated regularly.

A 24-page guide to WWPA lumber species and grades, structural design, and general wood properties, available as a free download from the association's website, www.wwpa.org.

Websites

American Institute of Timber Construction: aitc-glulam.org

American Wood Council: www.awc.org

American Wood Protection Association AWPA: www.awpa.com

APA–The Engineered Wood Association: www.apawood.org

Canadian Wood Council: www.cwc.ca

Composite Panel Association: www.pbmdf.com

Consortium for Research on Renewable Industrial Materials: corrim.org

Forest Stewardship Council: www.fsc.org

FPInnovations: fpinnovations.ca

Hardwood Manufacturers Association: www.hardwoodinfo.com

Hardwood Plywood & Veneer Association: www.hpva.org

Manufactured Housing Institute: www.manufacturedhousing.org

Modular Building Institute: www.modular.org

Nordic Structures: www.nordic.ca/en/home

Rainforest Alliance Sustainable Agriculture Certification: www.rainforest-alliance.org/business/sas

Structural Insulated Panel Association: www.sips.org

StructureCraft: structurecraft.com

Think Wood: www.thinkwood.com

U.S. Forest Products Laboratory: www.fpl.fs.fed.us

Western Wood Products Association: www.wwpa.org

Wood Database: www.wood-database.com

For the French American School, the move from temporary facilities to a permanent structure on the same site meant that construction had to take place, in full, between the end of one academic year and the start of the next. Modular construction was the only way to complete the work within the available four-month time span and have any hope of being ready for the school's September move-in date.

Architect Weinstein A|U's design for the building was driven by the constraints of the modular construction process, in which the factory-assembled building parts are trucked to the site and lifted into place by crane. The size of the modules was determined by highway regulations. In this case, width and height were strictly limited to 14 feet (4.3 m).

The architectural response was to accept the nature of the modules as simple box forms. The programmatic functions of the school were arranged into four "pods" containing classrooms, offices, and other major spaces, separated by smaller, connecting "gaskets" with bathrooms, stairs, and other service uses. The arrangement created a logical modulation of the building as a whole. Three of the pods would contain classrooms, while the fourth, nearest the entry, would be dedicated to public and school-wide functions: administrative offices, the library, and the multipurpose room (Figure A). Exterior, site-built elements, such as horizontal trim pieces to hold vines for a green wall and metal canopies to shade south-facing windows, were used to add scale and interest to the simplicity of the modular boxes themselves.

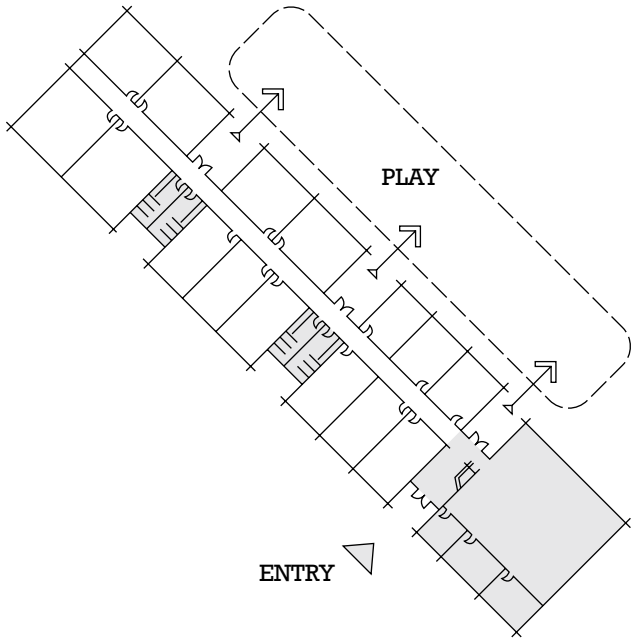


FIGURE A
The plan diagram consists of four pods connected by service links. Three of the pods house classrooms while the fourth contains administrative and public functions.

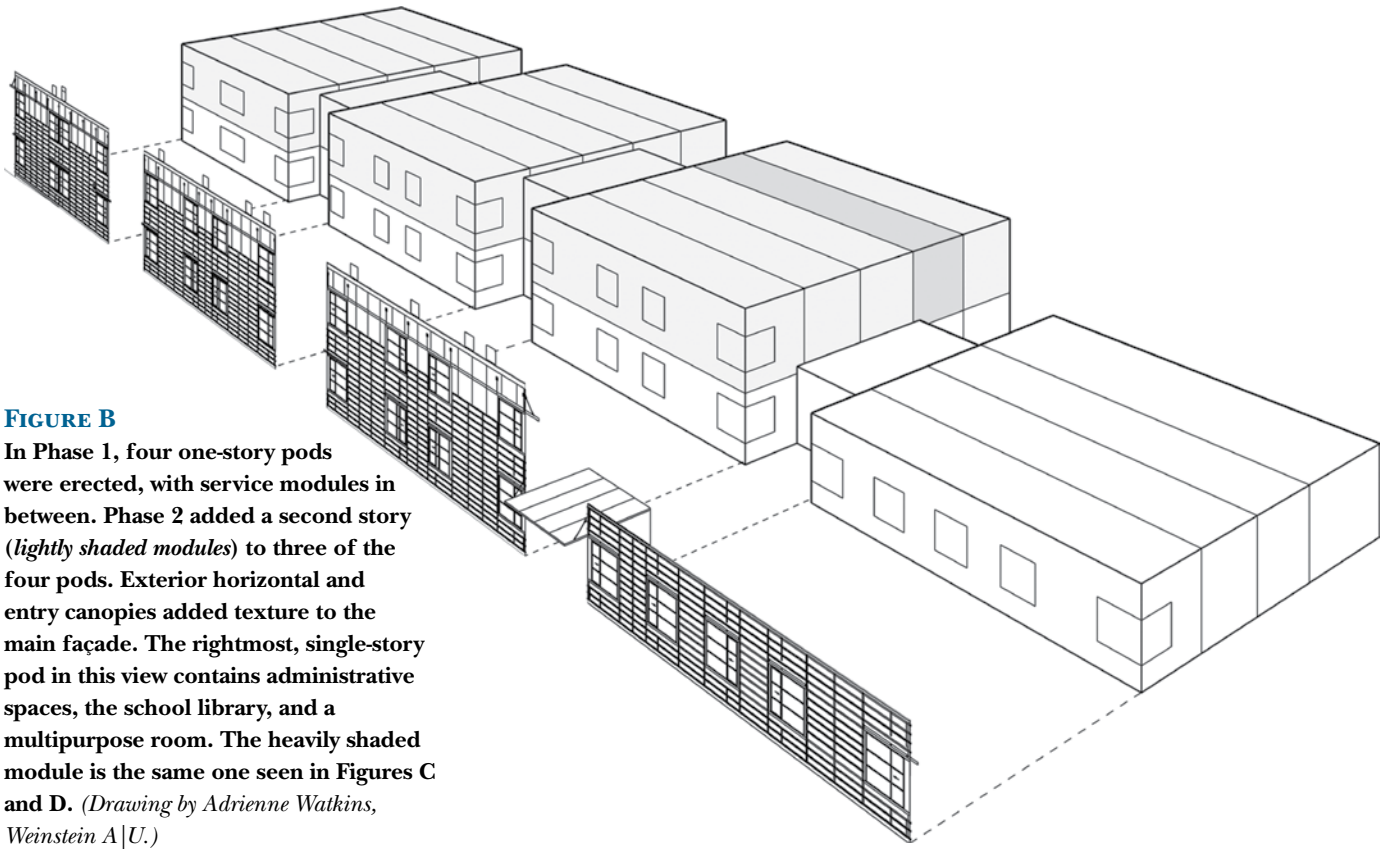


FIGURE B
In Phase 1, four one-story pods were erected, with service modules in between. Phase 2 added a second story (*lightly shaded modules*) to three of the four pods. Exterior horizontal and entry canopies added texture to the main façade. The rightmost, single-story pod in this view contains administrative spaces, the school library, and a multipurpose room. The heavily shaded module is the same one seen in Figures C and D. *(Drawing by Adrienne Watkins, Weinstein A|U.)*

The modular construction also lent itself to the project's need to be phased. The growing school needed only a portion of the building completed in the first few years, and fund-raising also necessitated stretching out development. The first phase would build out the entire planned footprint, but with only a single story. The later, second phase would add more second-floor classrooms to the three classroom pods. Because the second story was designed from the outset, the foundation and ground-floor modules were built to accommodate the stairs, elevator, plumbing, and structural loads that would come later when these additional modules were added (Figure B).

The stresses imposed on modules during transportation and lifting created additional design constraints. The number and size of openings for doors and windows were limited to maintain a sufficiently rigid structure. The design team worked closely with the manufacturer to maximize the size of important corner windows. Additionally, each module required full-depth floor and ceiling joist framing. As a result, when units were stacked, there would be redundant structure and added depth between floors that could have been avoided with site-built construction methods.

The modular units were built offsite, beginning in early spring. The day the students left in June, the work began on site. Difficulties in gaining building permits from the local building department were an unexpected challenge for the design team. The small, suburban jurisdiction had never before seen an application for construction of this type. Because the units would arrive on site with interior walls finished, state

FIGURE C

A module arriving on site. Each of 25 modules in Phase 1 and 19 modules in Phase 2 was individually trucked to the site from a factory located 30 miles away. Because there was no room on site to store modules, the modules were delivered "just in time" to be lifted into position shortly after their arrival. Temporary bracing straps and plywood stiffen the module during transportation and lifting. These are removed after the modules have been set in final position. Seen in this module is a corridor wall with doors and interior windows opening into classrooms. *(All photos by Joseph Iano.)*

FIGURE D

The same module seen in Figures B and C being lifted into position. This module was part of the Phase 2 expansion, so all work was performed without disturbing finished landscaping or site amenities already in place. This module contains half of three classrooms. The remainder of the classroom spaces is contained in an adjoining module not yet in place. The space above the finished ceiling houses mechanical equipment, ductwork, and the roof structural framing. Note the temporary crossbracing still in place during lifting.

agencies would inspect and approve structural, electrical, and plumbing systems that would be concealed by the time local inspectors first saw them. The design team had to work closely with the local agency to gain their confidence and assure them that all issues of concern would be properly addressed.

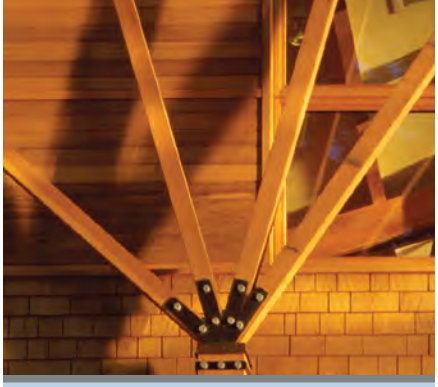
For the contractor, limited space available for staging construction on site, combined with overhead telecommunication and high-power electrical lines, presented special logistical difficulties. Module delivery was carefully scheduled so that modules could be lifted into final position as soon as they arrived at the construction site. Positioning and lifting of modules also had to be carefully planned to avoid conflicts with the overhead utilities that could not be relocated or interrupted.

The photograph of the completed project shows the modulation of the pod-and-gasket arrangement. Because the school is approached at an angle, this massing is easily visible. The corner windows were important features, to maximize light on the interior and reduce the "boxy" feel of the modules. If the project had been built using a conventional method, the size and location of the windows would not have been constrained. However, in a modular design, they created a weak point in the module and thus required special structural attention. This size was the largest possible within the system.

Special thanks to Weinstein A|U and Lesley Bain, principal, for their contributions to this case study.

Figure E

A projecting canopy marks the main entrance to the building. Smaller canopies provide shade for south-facing windows. The horizontal and vertical trim cover joint lines between modules and support growing vines that will, over time, create a green wall on the building façade. Note the corner windows, important for introducing daylight into the classrooms, which created structural difficulties that required special coordination between the design team and the module manufacturer.



4

Heavy Timber and Mass Timber Construction

- **Types of Construction**
  - Heavy Timber in the Building Codes
  - Sustainability and Heavy Timber and Mass Timber Construction
  - Mass Timber in the Building Codes
- **Fire Resistance of Large Wood Members**
  - Calculating the Fire Resistance of Wood Members
- **Traditional Heavy Timber Construction**
- **Contemporary Heavy Timber Construction**
  - Design of Heavy Timber Connections
  - Floor and Roof Decks
  - Walls
  - Lateral Stability
  - Accommodating Building Services
- **Mass Timber Construction**
  - Cross-Laminated Timber Panel Construction
  - Fire-Resistance Rated Connections
  - Lateral Stability
  - Protecting Mass Timber Structures during Construction
- **Wood–Concrete Composite Construction**
- **Longer Spans in Heavy Timber and Mass Timber**
  - Large Beams
  - Rigid Frames
  - Trusses
  - Arches and Domes
  - Preliminary Design of Heavy Timber and Mass Timber Structures

Architect Nils Finne combines heavy timber with robust stonework and finely detailed exterior finish carpentry in this well-crafted residence. *(Architect: FINNE Architects, www.FINNE.com; photo by Art Grice.)*

Wood beams have been used to span roofs and floors of buildings since the beginning of civilization. The first timber-framed buildings were crude pit houses, lean-tos, teepees, and basketlike assemblages of bent saplings. In earliest historical times, roof and floor timbers were combined with masonry loadbearing walls to build houses and public buildings. In the Middle Ages, braced wall frames of timber were built for the first time (Figure 4.1). The British carpenters who emigrated to North America in the 17th and 18th centuries brought with them a fully developed knowledge of how to efficiently build braced frames, and for two centuries North Americans lived and worked mostly in buildings framed with hand-hewn wooden timbers joined by interlocking wood-to-wood connections (Figure 4.2). Nails were rare and expensive, so they were used only in door and window construction and, sometimes, for fastening siding boards to the frame.

Until two centuries ago, logs could be converted to boards and timbers only by human muscle power. To make timbers, axemen skillfully scored and hewed logs to reduce them to a rectangular profile. Boards were produced slowly and laboriously with a long, two-man pit saw, one man standing in a pit beneath the log, pulling the saw down, and the other standing above, pulling it back up. At the beginning of the 19th century, water-powered sawmills began to take over the work of transforming tree trunks into lumber, squaring timbers and slicing boards in a fraction of the time that it took to do the same work by hand.

Most of the great industrial mills of 19th-century North America, which manufactured textiles, shoes, machinery, and many other goods of civilization, consisted of heavy sawn timber floors and roofs supported by masonry exterior walls (Figures 4.3 and 4.4). And the construction of heavy timber factories and other large buildings continued well into the 20th century, although at a diminishing rate as newer methods of steel and concrete construction became increasingly widespread.

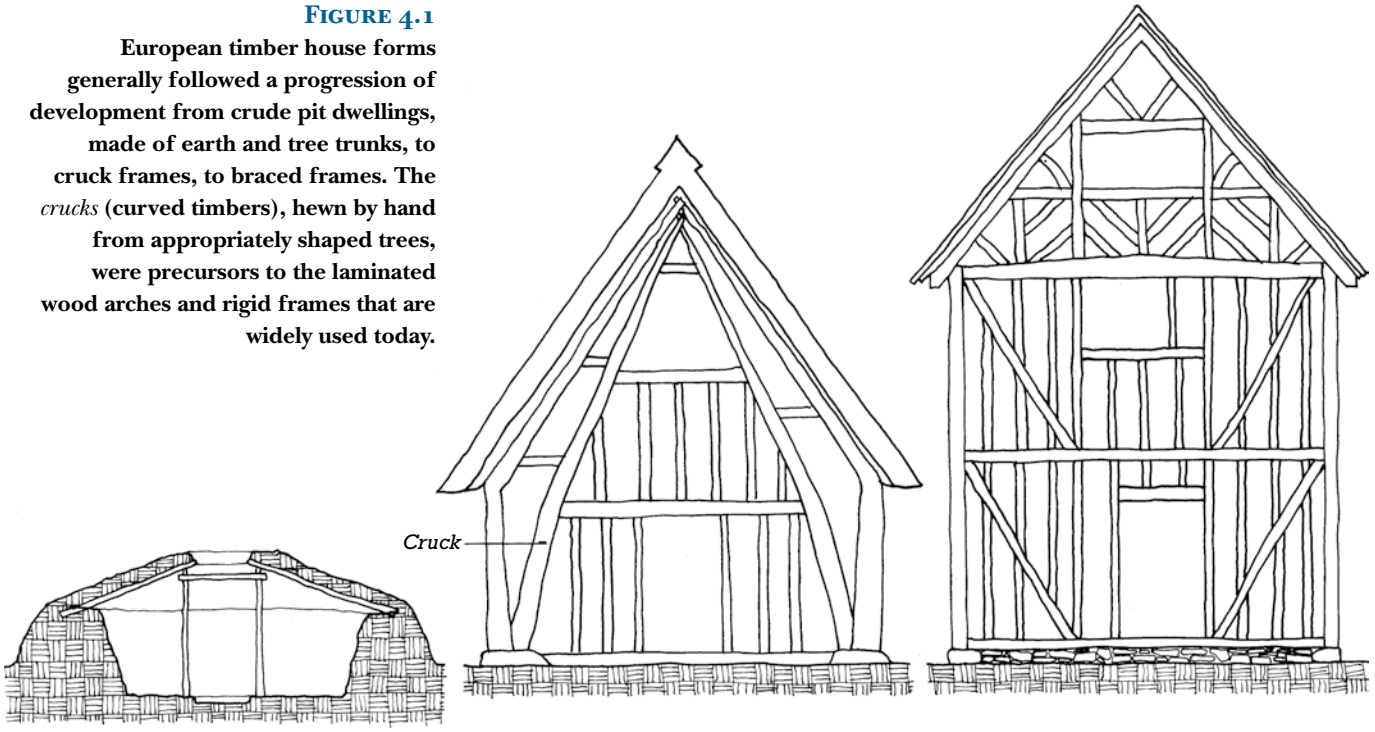
Today, this oldest of building materials is undergoing a modern renaissance. A deeper appreciation of the environmental benefits of wood construction, the development of manufactured wood components, and advances in the understanding of the performance of wood structures during building fires are opening up new possibilities for larger, more sustainable buildings constructed of this material. Combined with wood's innate structural efficiency and ease of construction, these new timber systems are poised to make a dramatic impact on building construction in North America.

Types of Construction

Contemporary *heavy timber frame* construction is a post-and-beam structural system made from large-dimension wood members that remains, in modern form, remarkably true to its 19th-century origins. Today, however, such structures may include glulams, structural composite lumber, and other manufactured wood products in addition to solid sawn wood members; a greater diversity of connector types are used; and exterior walls and roofs are constructed to meet today's more stringent building energy efficiency standards.

In this textbook, the term *mass timber* construction refers to wood structural systems that incorporate cross-laminated timbers, nail-laminated timbers, and other large format, loadbearing wood panels. (For more information about these component types, see Chapter 3.) While mass timber components can be used in conventional heavy timber frame construction, they are most notable for their potential application in the construction of taller buildings exceeding historical building code height and area limits for wood structures. Mass timber is a relatively new term to the building industry, and at this time its usage and definition vary among sources.

FIGURE 4.1
European timber house forms generally followed a progression of development from crude pit dwellings, made of earth and tree trunks, to cruck frames, to braced frames. The *crucks* (curved timbers), hewn by hand from appropriately shaped trees, were precursors to the laminated wood arches and rigid frames that are widely used today.



PIT DWELLING *CRUCK FRAME* *BRACED FRAME*

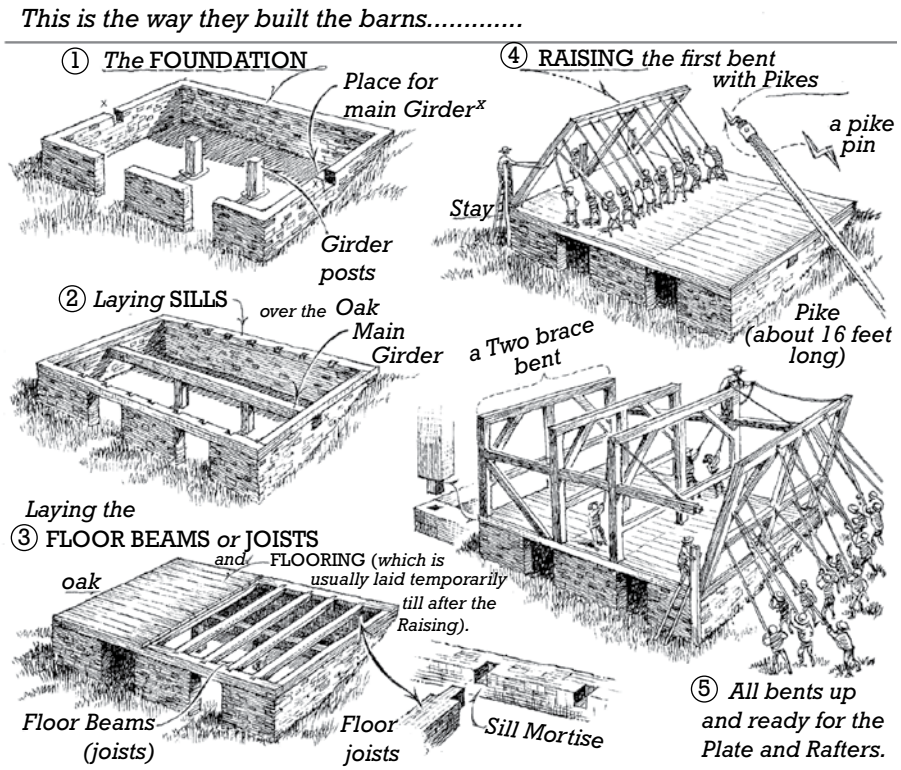


FIGURE 4.2
The European tradition of heavy timber framing was brought to North America by the earliest settlers and was used for houses and barns well into the 19th century. *(Drawing by Eric Sloane, courtesy of the artist.)*

Interactive Exercise

FIGURE 4.3
Most 19th-century industrial buildings in North America were constructed of heavy timber roofs and floors supported at the perimeter on masonry loadbearing walls, a construction method that came to be known as Mill construction. This impressive group of textile mills stretches for a distance of 2 miles (3 km) along the Merrimac River in Manchester, New Hampshire. *(Photo by Randolph Langenbach.)*

The old country builder, when he has to get out a cambered beam or a curved brace, goes round his yard and looks out the log that grew in the actual shape, and taking off two outer slabs by handwork in the sawpit, chops it roughly to shape with his side-axe and works it to the finished face with the adze, so that the completed work shall for ever bear the evidence of his skill. . . .

—Gertrude Jekyll, English garden designer, writing in 1900

FIGURE 4.4
The generously sized windows in the mills provided plenty of daylight to work by. Columns were of wood or cast iron. Most New England mills, like this one, were framed very simply: Their floor decking is carried by beams running at right angles to the exterior walls, supported at the interior on two lines of columns. Overhead sprinklers provide additional fire safety to a construction method that already has inherent fire-resistive qualities. *(Photo by Randolph Langenbach.)*

Heavy Timber in the Building Codes

In the International Building Code (IBC), heavy timber frame buildings are classified as *Type IV-HT (Heavy Timber) construction.* (For an explanation of building code construction types, see Chapter 1.) In this construction type, wooden structural members must meet minimum size requirements and exterior walls must be constructed of noncombustible or other suitably fire-resistant materials.

Sustainability and Heavy Timber and Mass Timber Construction

Especially as wood structural systems begin to compete with steel and concrete for use in taller buildings, this material has the potential to make significant new contributions toward reduction in building environmental impacts. For more information about the sustainability of wood products in general, see the Chapter 3 sidebar "Sustainability and Wood."

Building and Material Life-Cycle Impacts

- In many scenarios, heavy timber frame and mass timber structures are found to have lower embodied energy and more favorable carbon footprints than equivalent steel, concrete, or masonry structures. One life-cycle analysis study reports reductions in climate change impacts in the range of 15 to 65 percent for mass timber buildings up to 21 stories tall when compared to comparable concrete structures over a 60-year lifetime.
- An environmental building declaration prepared for the Design Building at UMass Amherst, a four-story, 88,000 square foot (8100 m^2) structure framed with cross-laminated timber, glulam, and structural steel, reports the following cradle-to-grave impacts over a 60-year lifetime:

Nonrenewable primary energy consumption	1100 MJ/m^2 (97,000 BTU/sf)
Global warming potential (carbon sequestration included)	63 kg/m^2 (13 lb/sf) CO_2 eq.
Fresh water consumption	180 L/m^2 (4.5 gal/sf)

- The medium-span structural systems typical of heavy timber frame and mass timber construction lend themselves to future adaptability for a broad variety of uses, potentially extending the useful lifetime of the building. Many 19th- and early 20th-century heavy timber buildings remain productively useful to this day.
- Solid timbers can be recycled from mills, factories, and barns when these buildings are demolished. Most of these timbers originated from old-growth forests in which trees grew slowly, producing fine-grained, dense wood with structural properties superior to those of today's new-growth timbers. Recycled timbers may be used as is, resurfaced to give them a new appearance, or resawn into smaller members. However, any old metal fasteners retained in the timbers must be meticulously found and removed, because they can cause expensive damage to saw blades and planer knives.

The minimum permitted sizes for wood components in Type IV-HT construction are summarized in Figure 4.5. Exterior walls may be of concrete, masonry, or a steel frame with metal or other noncombustible cladding. Or, in some cases, fire-retardant-treated wood, cross-laminated timber, or other large wood members may also be permitted. The International Building Code limits this construction type to six stories or less.

Heavy timber framing may also appear in other building code construction types where smaller wood members are permitted, including Types III and V, as long as the building complies with the more restrictive height and area limits of these types. In this way, heavy timber framing can appear in all manner of smaller, residential, commercial, and institutional buildings (Figure 4.6).

	Supporting Floor Loads	Supporting Roof Loads Only
Solid wood columns	8 × 8 nominal (190 × 190 mm)	6 × 8 nominal (140 × 190 mm)
Glulam columns	6¾" × 8¼" (171 × 210 mm)	5" × 8¼" (127 × 210 mm)
Solid wood beams and girders	6 × 10 nominal (140 × 241 mm)	4 × 6 nominal (89 × 140 mm)
Glulam beams and girders	5" × 10½" (127 × 267 mm)	3" × 6 ⅞" (76 × 175 mm)
Solid wood or glulam decking	3× nominal (64 mm)	2× nominal (38 mm)
NLT decking	4× nominal (89 mm)	3× nominal (64 mm)
CLT decking	4" (102 mm)	3" (76 mm)
CLT wall panels	4" (102 mm)	4" (102 mm)

Figure 4.5
Minimum sizes for wood components in Type IV-HT construction according to the International Building Code. Minimums for structural composite lumber members generally fall in between those for solid wood and glulams. When used in exterior walls, CLTs must be covered on their outside face with a layer of gypsum sheathing or other fire-protective material.

FIGURE 4.6
Sea Ranch Condominium 1. Each attached dwelling at Sea Ranch, in northern California, is framed with a simple cage of unplaned heavy timbers sawn from trees taken from another portion of the site. The diagonal members act as wind and seismic braces. *(Architect: Moore Lyndon Turnbull Whitaker. Photo by Edward Allen.)*

Mass Timber in the Building Codes

The current (2018) version of the International Building Code (IBC) does not recognize mass timber as a separate construction type, but this will change in future versions of this code. At the time of this writing, three new construction types have been approved by the International Code Council for incorporation into future versions of the IBC, with building height limits of as high as 18 stories (Figure 4.7).

A similar code change process is also occurring at this time with Canada's model code, the National Building Code of Canada. Recognition of mass timber construction along with increases in building height and area limits are expected to be adopted in an upcoming version of this code.

Construction Type	Fire Resistance	Type of Fire Protection	Maximum Height
IV-A	Primary Frame: 3 hours Floors: 2 hours	Applied fire protection must provide at least 2/3 of the required fire resistance.	18 stories 270 ft (82 m)
IV-B	Primary Frame: 2 hours Floors: 2 hours	Applied fire protection must provide at least 2/3 of the required fire resistance, except limited areas may rely solely on the fire resistance of the wood members.	12 stories 180 ft (55 m)
IV-C	Primary Frame: 2 hours Floors: 2 hours	Most mass timber components may rely solely on the fire resistance of the wood members.	9 stories 85 ft (26 m)

FIGURE 4.7
An overview of new construction types that will appear for the first time in the 2021 International Building Code. Applied fire protection refers to one or more layers of gypsum wallboard or other noncombustible, fire-protective material applied directly over the wood components and their connections (encapsulation). Height limits shown in this table are for Business occupancy, fully sprinklered buildings. Limits vary with occupancy and whether a fire sprinkler system is provided. Material and protection requirements for vertical shafts and other technical requirements also vary among the three types.

Fire Resistance of Large Wood Members

Traditional heavy timber frame structures rely on the natural resistance of large wood members for protection from fire. Compared to smaller pieces of wood, larger members are slow to catch fire and burn. And when large members do burn, the burnt layer, or *char*, that forms on their exposed faces continues to insulate and protect the inner portions. This allows the member to survive and function, although at somewhat reduced strength, for an extended period of time during a building fire (Figure 4.8, *left*). For example, a heavy timber beam, though deeply charred by gradual burning, will maintain sufficient capacity to carry loads long after an unprotected steel beam exposed to the same conditions has lost strength and failed. For these reasons, building codes recognize heavy timber framing as roughly equivalent in fire safety to steel,

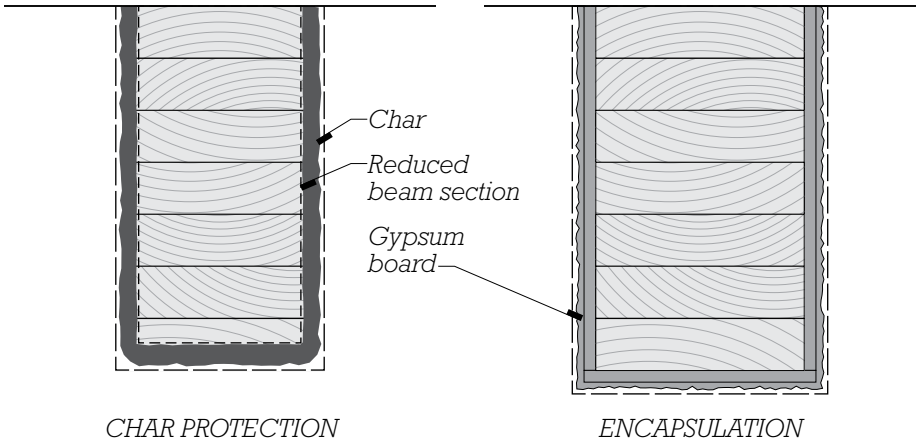


Figure 4.8

Fire protection of a glulam beam. *Left*: Char protection relies on the slow-burning characteristics of large wood members. During a fire, the outer char layer slowly progresses inward while continuing to protect the inner unaffected portions of the beam. *Right*: Encapsulation relies on a fire-resistive covering. Once this noncombustible covering is consumed, charring can protect the member for an additional period of time. After a significant fire, heavily charred members may need to be repaired or replaced.

Calculating the Fire Resistance of Wood Members

A wood structural member may be designed to rely solely on encapsulation, solely on charring, or a combination of both to meet required fire resistance ratings.

In the International Building Code, each layer of Type X gypsum board, ½-inch (13-mm) thick, can be assumed to provide 25 minutes of fire protection to a large wood member, and a ⅝-inch (16-mm)-thick board, 40 minutes of protection. So, for example, a mass timber member can be provided with two hours of encapsulated protection by covering its exposed surfaces with three layers of ⅝-inch (16-mm) Type X gypsum board. (See Chapter 23 for more information about gypsum board types.)

Different methods may be used to determine char protection. Typically, calculations begin with a determination of the member's *effective char rate*. For example, a nominal char rate of 1.5 inches (38 mm) per hour may be assigned, and then adjusted to account for changes in the rate of charring over time, the faster advance of charring at sharp corners, weakening of heated wood close to the charred layer, and in some cases, lamination thickness of the member. Considering a heavy timber beam exposed to fire for one hour, the effective char depth may then be determined to be 1.8 inches (46 mm). This amount of material is subtracted from the exposed faces of the beam and the strength of the beam at this reduced size is compared to the loads that the beam must support. If the beam proves too weak at this reduced size, the full size is increased as needed. In many cases, heavy timber beams designed to meet normal strength and stiffness criteria can achieve 1 hour of fire resistance with little or no additional size increase. On the other hand, spanning members requiring 90 minutes or more of protection, as well as many columns with as little as a 1-hour rating, are likely to require an increase in size to maintain adequate capacity in a charred state.

When a mass timber member is designed to rely on both encapsulation and char for its fire resistance, the contribution of each is added together. For example, to meet a 2-hour fire resistance rating, two-thirds of the protection, or 80 minutes, may be provided by two layers of ⅝-inch (16-mm)–Type X gypsum board (2 × 40 minutes = 80 minutes), and the member itself designed to provide forty additional minutes of protection through charring.

concrete, or masonry with a 1-hour fire resistance rating.

In taller mass timber buildings, wood members may be covered with noncombustible fire-resistive materials to provide additional fire protection. This *encapsulation* most frequently takes the form of one or more layers of gypsum board applied directly to the faces of the members (Figure 4.8, *right*). During a fire, while these materials provide protection, the wood member remains unaffected and at full strength. Once these materials are consumed, charring can provide additional protection.

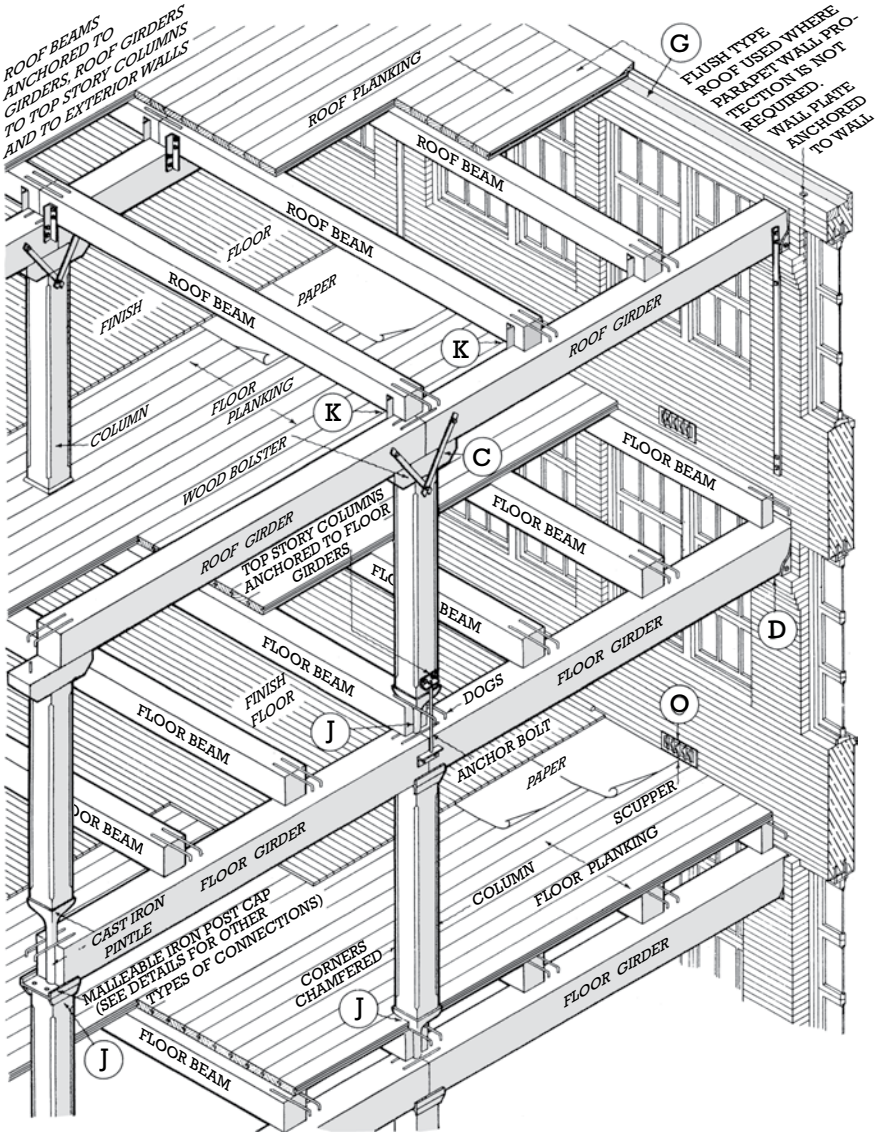
In Type IV Heavy Timber construction, encapsulation of wood members is not required and the minimum required member sizes (Figure 4.5) are assumed to provide sufficient fire resistance through charring. In Types IV-A, IV-B, and IV-C construction, wood members must meet the same minimum dimension requirements. But, unlike Type IV-HT construction, they must also meet prescribed minimum fire resistance ratings (Figure 4.7). In Type IV-C construction, the required fire resistance can, in most cases, be met entirely by charring. In Types IV-B and IV-A construction, fire resistance must be provided by a combination of encapsulation and charring, or by encapsulation alone.

Unlike most other structural materials, there is not an extensive history of tested assemblies to draw from when designing fire-resistance rated mass timber components. Instead, fire resistance is more often calculated for each type and size of member, taking into account the actual loads on the member, protective capacity of any applied materials and, if relying on wood charring, the rate of charring in a fire scenario and the gradual reduction in the capacity of the member. These calculation methods themselves have been verified through large-scale laboratory tests and are used to ensure that the wood structure will retain sufficient structural capacity even after a fire event of the specified duration.

Traditional Heavy Timber Construction

An example of traditional *Mill construction*, the precursor to modern Type IV Heavy Timber construction, is illustrated in Figures 4.9 through 4.11. Exterior walls are constructed of noncombustible solid masonry, interior framing is heavy timber, floor and roof decks are heavy planks covered with a layer of finish flooring, and connections between members are completed with various iron and steel components.

Girder–column connections are designed so that columns do not rest on the girders. (The reasons for this are discussed in more detail later in this chapter.) Where beams and girders rest on exterior masonry walls, beam ends are *firecut*, that is, cut at a sloping angle, so that in the case of fire and collapse of the floor framing, the ends of the beams can readily fall from the masonry wall pocket without destabilizing the wall itself. An air space around the beam ends helps to protect the beam from moisture in the surrounding masonry.



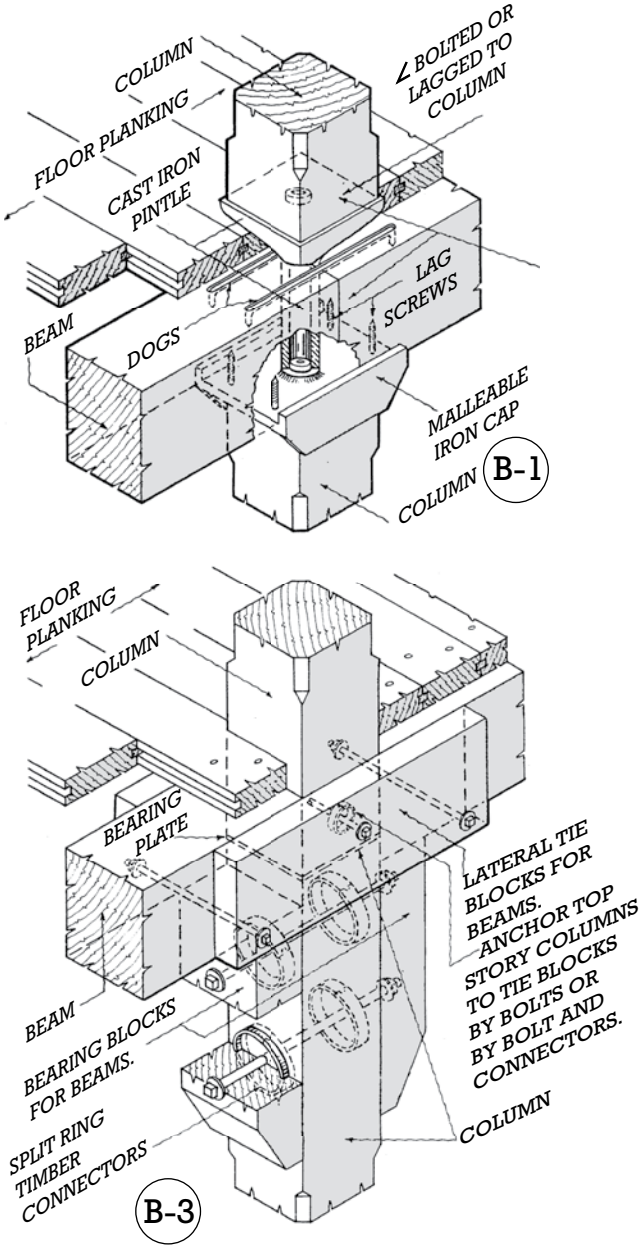


Figure 4.9

(*Opposite page*) Traditional Mill construction. Exterior walls are constructed of noncombustible, solid masonry. Interior framing is heavy timber. Iron dogs tie beams and girders together at their ends. A long steel strap anchors the roof girder sufficiently low in the outside wall that the weight of the masonry above the anchor point is enough to resist wind uplift on the roof. *(Heavy Timber construction details courtesy of the National Forest Products Association, Washington, DC)*

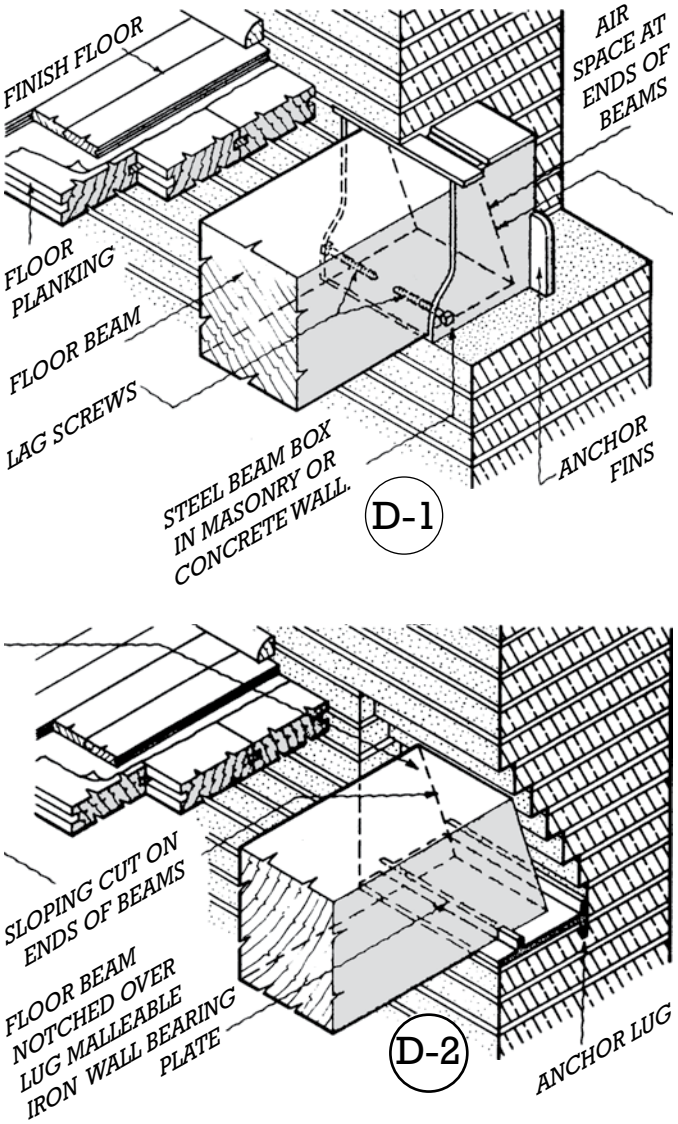


Figure 4.10

(left) Heavy timber girder–column connections are designed so that column loads are transferred between column sections without bearing on girders. Detail B-1 avoids resting the column on the beam with a cast iron pintle. In detail B-3, the upper column passes through the beam with only a steel bearing plate between it and the column below. Also in B-3, split-ring connectors are used to form a connection between the bearing blocks and the columns strong enough to support the loads from the beams; it would take a much larger number of bolts to do the same job. *(Heavy Timber construction details courtesy of the National Forest Products Association, Washington, DC)*

Figure 4.11

(right) Details for wood beam ends bearing on masonry. The beam ends are firecut and anchored to the wall by means of either lag screws (D-1) or a lug (D-2) on the iron bearing plate. *(Heavy Timber construction details courtesy of the National Forest Products Association, Washington, DC)*

Contemporary Heavy Timber Construction

Design of Heavy Timber Connections

Heavy timber connections should:

- Where possible, avoid loadbearing fasteners and rely on direct bearing between wood members and connectors
- Allow for wood shrinkage
- Avoid horizontal wood members in the vertical load path

Heavy timber connections that rely on direct bearing are more efficient and economical than those that that depend on mechanical fasteners for the transfer of loads between members. Figure 4.12*A* illustrates a beam–girder connection. As shown in (*B*), the beam end bears on the seat of the steel plate hanger and the hanger bears on the girder. In this configuration, the fasteners serve to hold members in position but are not loadbearing.

Heavy timber connections must account for shrinkage in the wood members. Figure 4.13 illustrates a connection similar to that in Figure 4.12. However, as the beam shrinks and is restrained by the fastener placed high in the hanger, the beam is lifted off its bearing. This causes tensile stress perpendicular to the grain of the beam (the wood's weakest axis) and splitting of the wood member. This configuration becomes increasingly problematic as the depth of the beam and distance between fastener and bearing increase.

Figure 4.14 illustrates a beam–column connection that relies on the same recommended design strategies: Beam ends bear directly on a steel plate saddle and the saddle bears on the column, fasteners serve as positional aids only, and

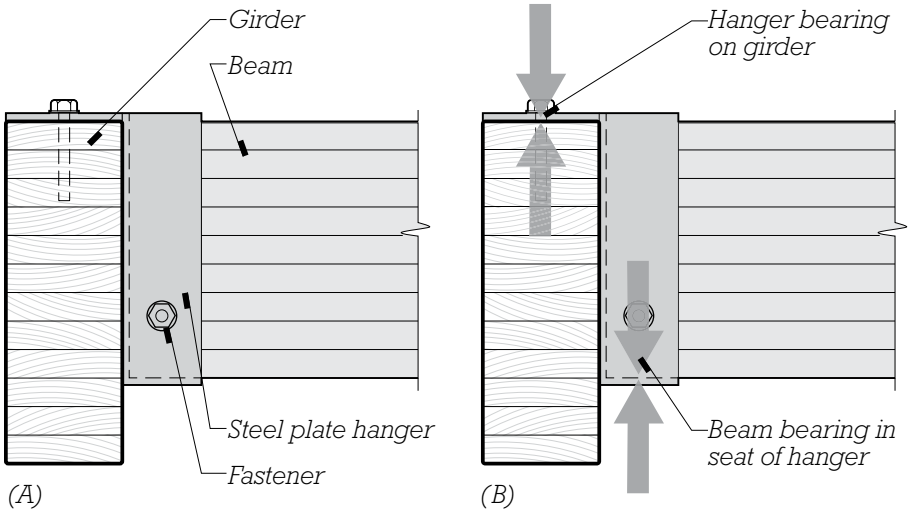


Figure 4.12
(*A*) A steel plate hanger beam–girder connection. (*B*) Loads are transferred through the connection where the beam rests on the bottom of the U-shaped hanger and the hanger rests on the top of the girder.

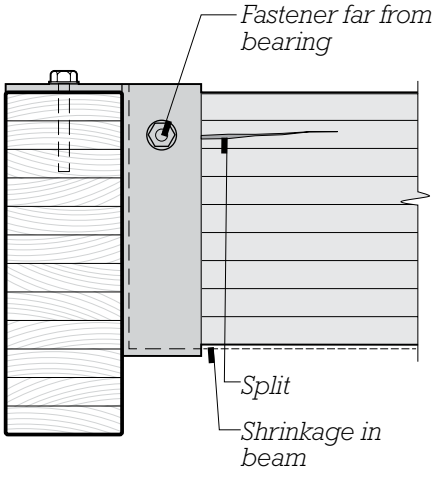


Figure 4.13
Poor fastener placement. As the beam fastener is moved farther from the beam bearing, wood shrinkage causes the beam to lift, resulting in tension perpendicular to the grain of the wood and splitting.

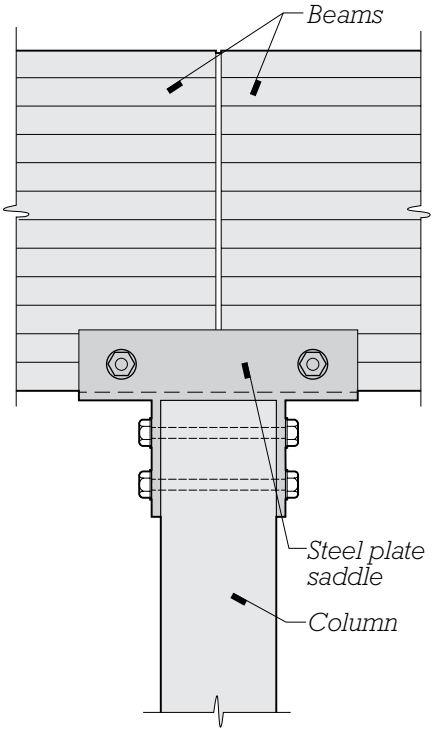


Figure 4.14
A beam–column connection that relies on direct bearing between the beams and a steel plate connector, and between the connector and column.

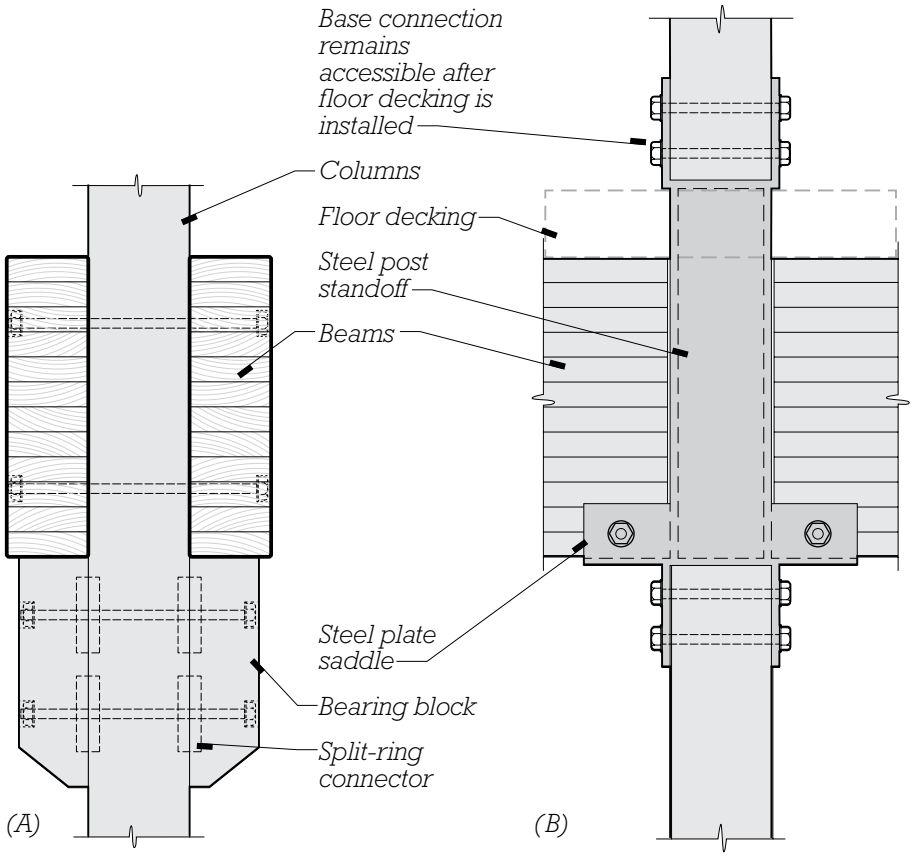


FIGURE 4.15

Multistory column connections. (*A*) The column is continuous through the connection. Fastener ends are countersunk for a cleaner appearance. The bearing block connections to the column rely on split-ring connectors, a type of loadbearing fastener discussed later in this section. (*B*) A steel post standoff connects columns above and below the floor platform.

Interactive Exercise

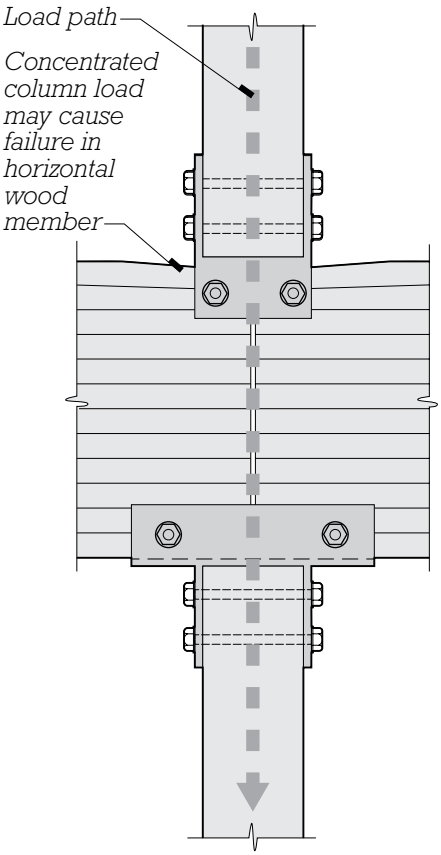


FIGURE 4.16

An incorrectly designed column and beam connection. The concentrated load from the column may exceed the compressive strength of the beam perpendicular to the grain of the wood, and shrinkage in beams accumulates from floor to floor.

shrinkage in the wood members is unrestrained.

Figure 4.15 illustrates beam–column connections for a multistory structure. In (*A*), the column is continuous through the connection. Paired beams straddling the column are supported on *bearing blocks*. The bolts through the beams are not loadbearing. Where restraint of shrinkage is a concern, the bolt holes can be slightly oversized. (The split-ring connectors attaching the bearing blocks to the column are loadbearing.) In (*B*), columns are only as tall as each floor and a steel post standoff completes the connection between floors. The top of the standoff is raised above the level of the floor decking so that this part of the connection can be completed after the decking is installed and a convenient, safe working surface is in place.

Figure 4.16 illustrates a horizontal wood member inserted into the vertical load path. Because wood is roughly three times weaker in compression perpendicular to grain (as in the beam) than parallel to grain (as in the column), the concentrated column load may cause failure in the beam. Even absent wood failure, this connection is problematic because of the greater wood shrinkage that occurs perpendicular to grain. Where beams and columns are stacked, the beam shrinkage at each floor level accumulates, and at upper floor and roof levels the dimensional movements become unacceptably large.

FIGURE 4.17
Canted exterior glulam columns supporting paired glulam roof beams at the Washington Fruit & Produce Company, by Graham Baba Architects and MA Wright Structural Engineers. Column bases rest on round steel tube standoffs. Exposed beam ends are protected with metal flashing. *(Photo by Kevin Scott.)*

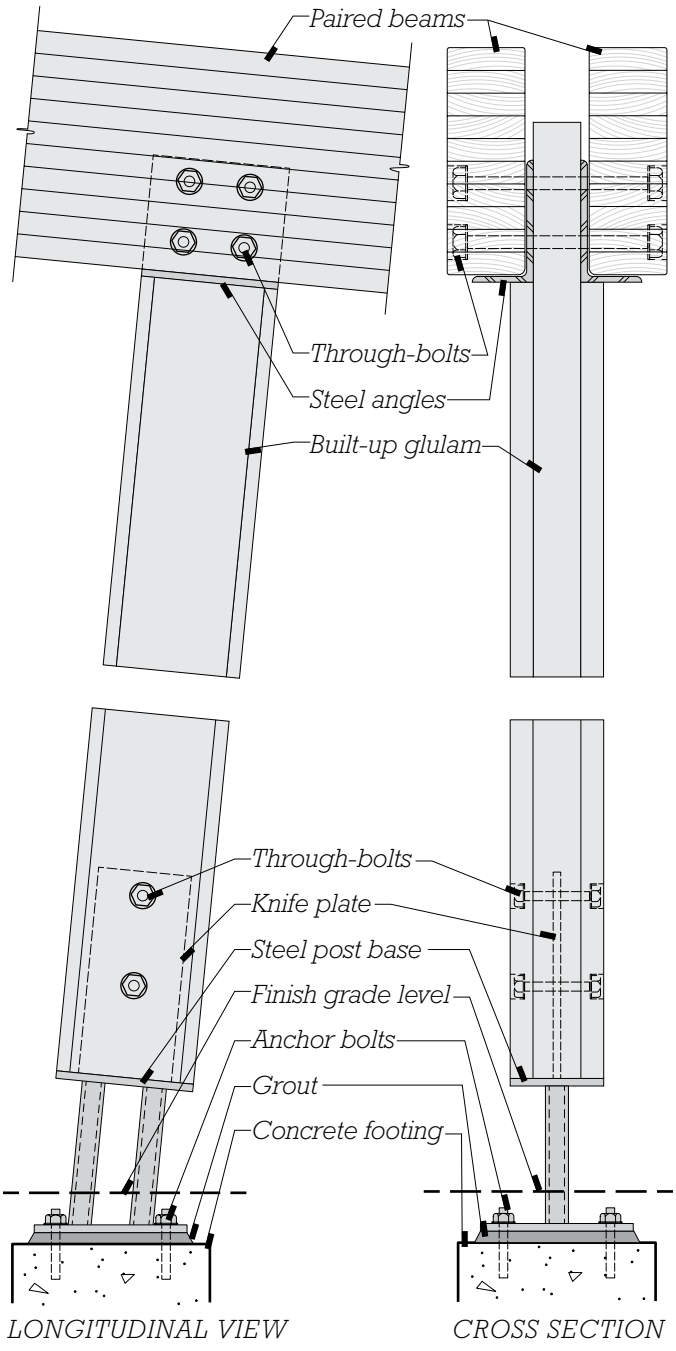


FIGURE 4.18
Sectional views of the columns pictured in Figure 4.17. At the base is a knife plate connection. The bolts are nonloadbearing positional aids. The built-up columns consist of standard glulam members with added solid nominal 2-inch (38-mm) members laminated to either side. Beam–column connections are direct bearing, similar to the connection shown in Figure 4.15 but with the addition of steel support angles.

Figures 4.17 and 4.18 illustrate heavy timber columns with *knife plate* base connections. The thin steel plates are inserted into machined slots within the wood column and fixed in place with through-bolts. Knife plate connections present a cleaner appearance compared to fully exposed metal connections. When combined with loadbearing fasteners, they can produce a stronger connection. And by embedding parts of the connector deep within the wooden member where they can be protected from the heat of fire, this design can contribute to a connection with greater fire resistance.

Loadbearing Fasteners in Heavy Timber Connections

Loadbearing fasteners are most suitable for heavy timber connections where direct bearing between members is not practical, where connections are subject to tensile forces, or where a highly ductile connection is required, such as when part of a seismic force resisting system. While traditional bolts may be used in such connections, the generous spacing requirements for bolts, necessary to avoid splitting of wood members, makes alternative fastener types often more compact and efficient.

Figures 4.19 and 4.20 illustrate a steel dowel and knife plate connector. Compared to bolts, a greater number of smaller diameter, more closely spaced dowels are used. The dowels are self-drilling, eliminating play in the connection and simplifying assembly. Toothed plates, split-ring connectors, and timber rivets, all of which are discussed in Chapter 3, are other loadbearing fastener types.

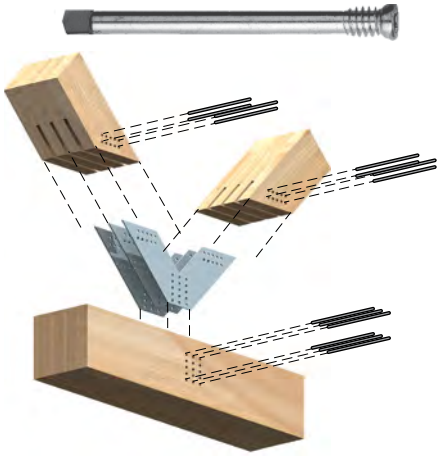


FIGURE 4.19
Loadbearing, self-drilling steel dowels (top) are used with steel knife plates to create a high-strength heavy timber connection. Using multiple knife plates creates a stronger connection. *(Courtesy of SFS Intec, Inc., Wyomissing, PA,* **www.sfsintecusa.com.)**

FIGURE 4.20
A completed heavy timber truss joint using the fastening system illustrated in Figure 4.19. *(Courtesy of SFS Intec, Inc., Wyomissing, PA,* **www.sfsintecusa.com**.*)*

Exterior Connections

Where heavy timber connections are exposed to the exterior, the wood members and connectors must be protected from moisture. In Figures 4.18 and 4.21, steel bases support the bottom of columns above an exterior surface. This raises the wood members above the wet surface and acts as a barrier between moisture and the vulnerable end grain of the wood. The steel connector is protected against corrosion by galvanizing, a durable, corrosion-resistant paint coating, or by the use of stainless steel.

In Figure 4.22, sheet metal flashings protect the top surfaces and ends of unsheltered beams exposed to precipitation. Exposed wood members may also be treated with preservative to improve resistance to decay and insect attack.

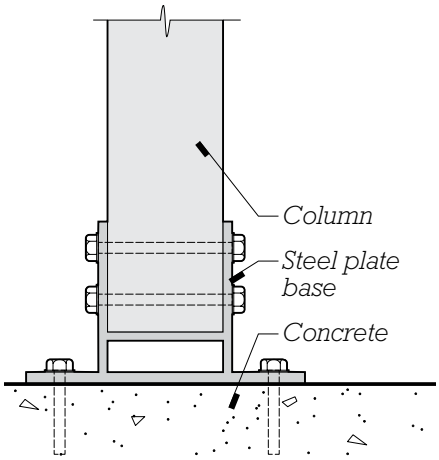


FIGURE 4.21
A steel column base connection raises the vulnerable end of the column above the ground and protects it from moisture.

FIGURE 4.22
Sheet metal flashing protects rafter tails exposed to the weather. *(Photo by Joseph Iano.)*

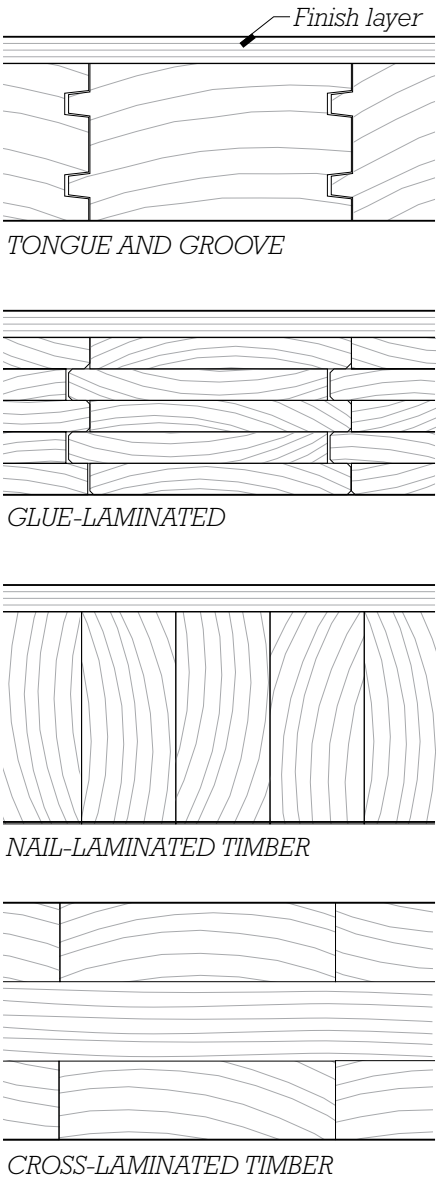


FIGURE 4.23
Four types of decking that qualify for Type IV Heavy Timber construction. The finish layer required on some types acts as an added barrier to the passage of hot gasses and smoke between floors during a building fire.

FIGURE 4.24
A glue-laminated wood building frame with diagonal bracing to resist lateral forces. This five-story University of British Columbia classroom building was permitted to be constructed in significant part of heavy timber based on modeling of the wood structure's performance that demonstrated fire resistance comparable to alternative noncombustible structural systems. Floor plates are composite concrete-CLT construction, discussed later in this chapter. *(Courtesy of Structurlam, Inc.)*

Floor and Roof Decks

Building codes require that Type IV Heavy Timber buildings have floors and roofs of solid wood construction without concealed combustible cavities. Minimum permissible thicknesses of decking are given in Figure 4.5 and some examples of decking types are illustrated in Figure 4.23.

To better resist the passage of hot gasses and smoke between floor levels, solid wood, glulam, and NLT decking must also be covered with a finish layer consisting of nominal 1-inch (19-mm) tongue-and-groove boards laid diagonally or at right angles to the decking, or one of several types of ½-inch (13-mm) wood panels.

Walls

In Type IV Heavy Timber construction, walls must be constructed of at least two layers of boards, each not less than 1 inch (25 mm) thick, laminated crosswise, cross-laminated or nail-laminated timber panels at least 4 inches (102 mm) thick, or other 1-hour fire-resistance-rated construction.

Lateral Stability

A heavy timber frame building with exterior masonry or concrete bearing walls may be braced against wind and seismic forces by the lateral resistance of the exterior walls. Or, diagonal bracing (Figure 4.24) or interior shear walls, such as around vertical circulation and utility cores, may be provided. Seismic upgrades to historical heavy timber and masonry buildings often require the insertion of new steel-braced frames or reinforced concrete shear walls and strengthening of floor plates in order to meet contemporary lateral force resistance requirements.

Accommodating Building Services

Heavy timber buildings pose special problems for the designer because they do not readily provide the cavities that are present in most other building systems and used to conceal building services. Roof thermal insulation cannot be hidden between ceiling joists or roof rafters and, instead, must be placed on top of the roof deck. Electrical wiring for overhead lighting fixtures must either run through exposed metal conduits below the roof or floor deck, which may be visually unsatisfactory, or be channeled within the deck. Ductwork for heating and cooling must also remain exposed (Figure 4.25).

Where concealed combustible spaces are created in Type IV Heavy Timber buildings, these spaces must be protected against the undetected spread of fire. For example, where ceiling or wall finishes are attached with furred construction, mineral-fiber insulation or other *fireblocking* materials must be installed within the concealed spaces. Or, where ceilings are suspended below heavy timber floors or roofs, sprinklers may be required in the space above the ceiling.

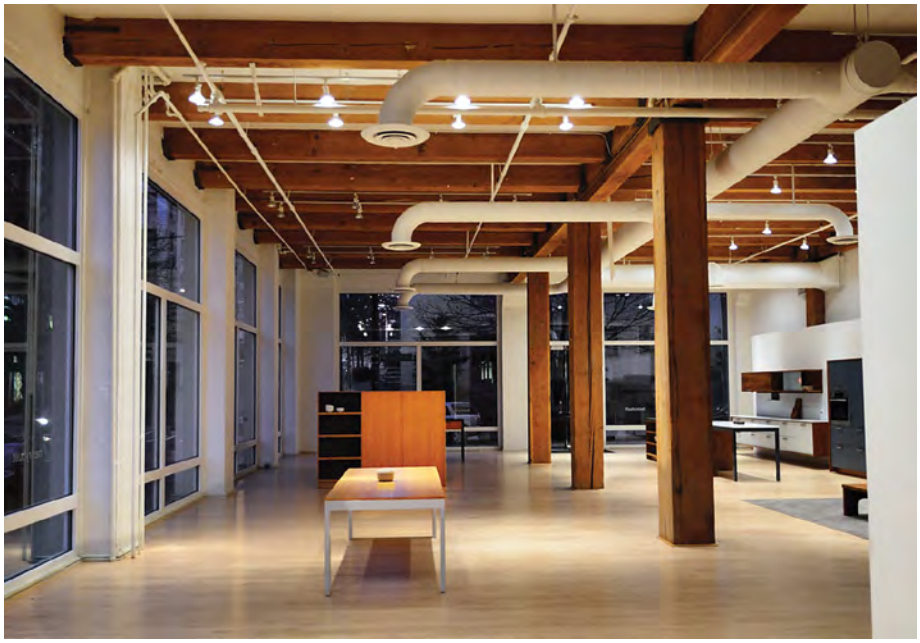


Figure 4.25
When floors and roofs are heavy timber framed, much of the lighting, ductwork, fire sprinklers, and other building services remain exposed to view and must be designed with appropriate care. *(Photo by Joseph Iano.)*

Figure 4.26
A CLT wall panel being lifted into position. Note the cutouts already completed in the panel for window rough openings and roof beam pockets. *(Courtesy of Structurlam, Inc.)*

Mass Timber Construction

As noted previously, in this textbook mass timber construction refers to wood structural systems incorporating cross-laminated timber or other large format, loadbearing wood panels, and is often associated with structures exceeding the building code height limits of conventional heavy timber frame construction.

Cross-Laminated Timber Panel Construction

Cross-laminated timbers are fabricated to the required size and shape at the factory. To the greatest extent possible, window and door openings in walls, shaft openings in floors, panel edge profiles, channels and cutouts for conduit, piping, and other building services, and other modifications are completed before panels are shipped to the construction site.

Once panels arrive on site, they are erected with small crews, simple tools, and lightweight lifting machinery (Figure 4.26). Erection also proceeds rapidly. For example, the seventeen timber-framed stories of the Brock Commons tower illustrated in Figure 4.30 were erected by a crew of nine, at an average rate of two floors per week, greatly exceeding the pace feasible with cast-in-place concrete systems.

Panel-to-panel connections commonly rely on long self-drilling screws, or nails or screws in combination with sheet metal connectors. Where needed, bolts, split rings, shear plates, metal plate connectors, or other heavier devices are used as well. Panel joints at the exterior are made airtight with the application of foam tape or continuous lines of sealant between panels as they are assembled. Interior panel joints may be similarly sealed to reduce sound transmission through walls and floors (Figures 4.27 and 4.28).

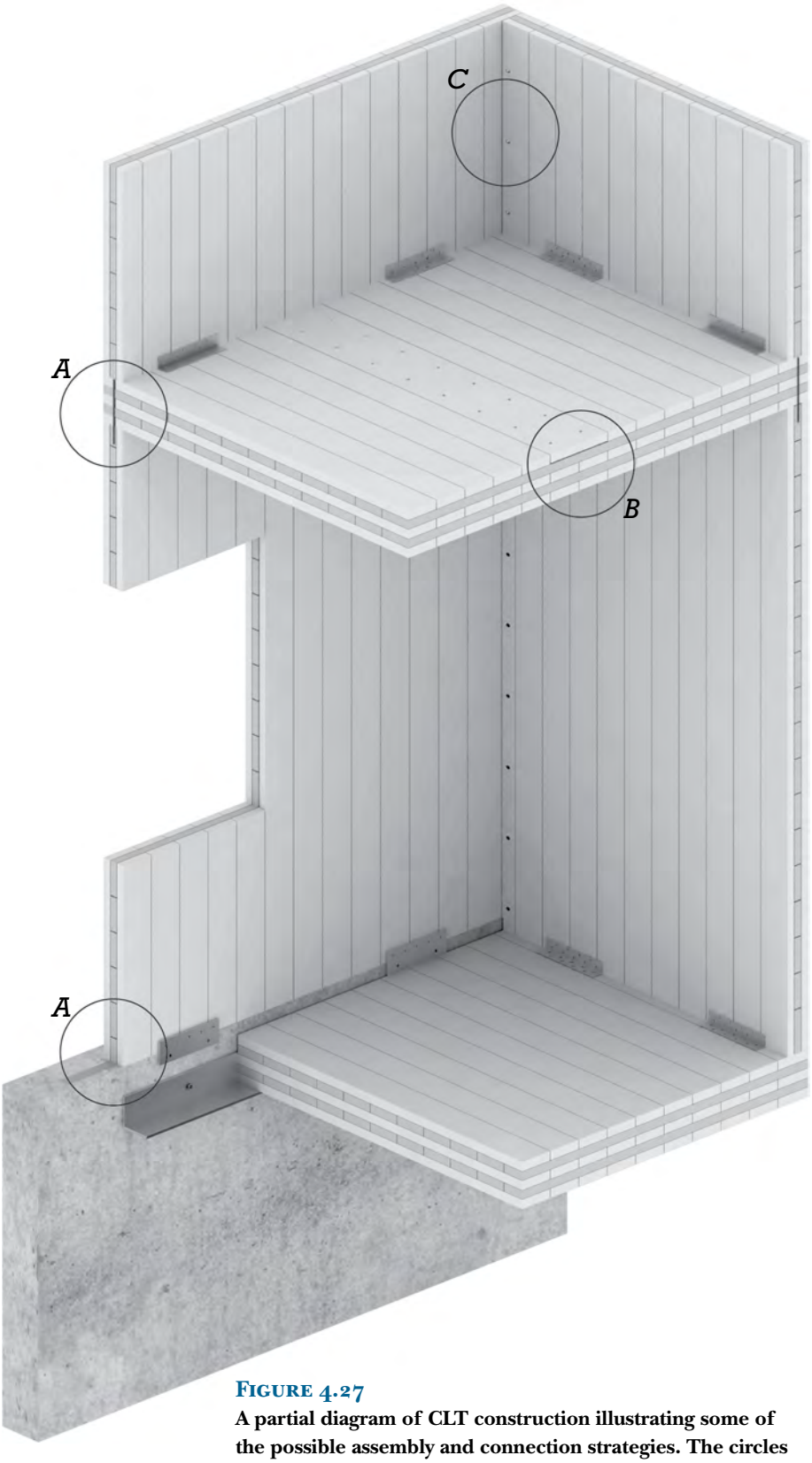


Figure 4.27
A partial diagram of CLT construction illustrating some of the possible assembly and connection strategies. The circles labeled *A*, *B*, and *C* refer to details in Figure 4.28.

Interactive Exercise

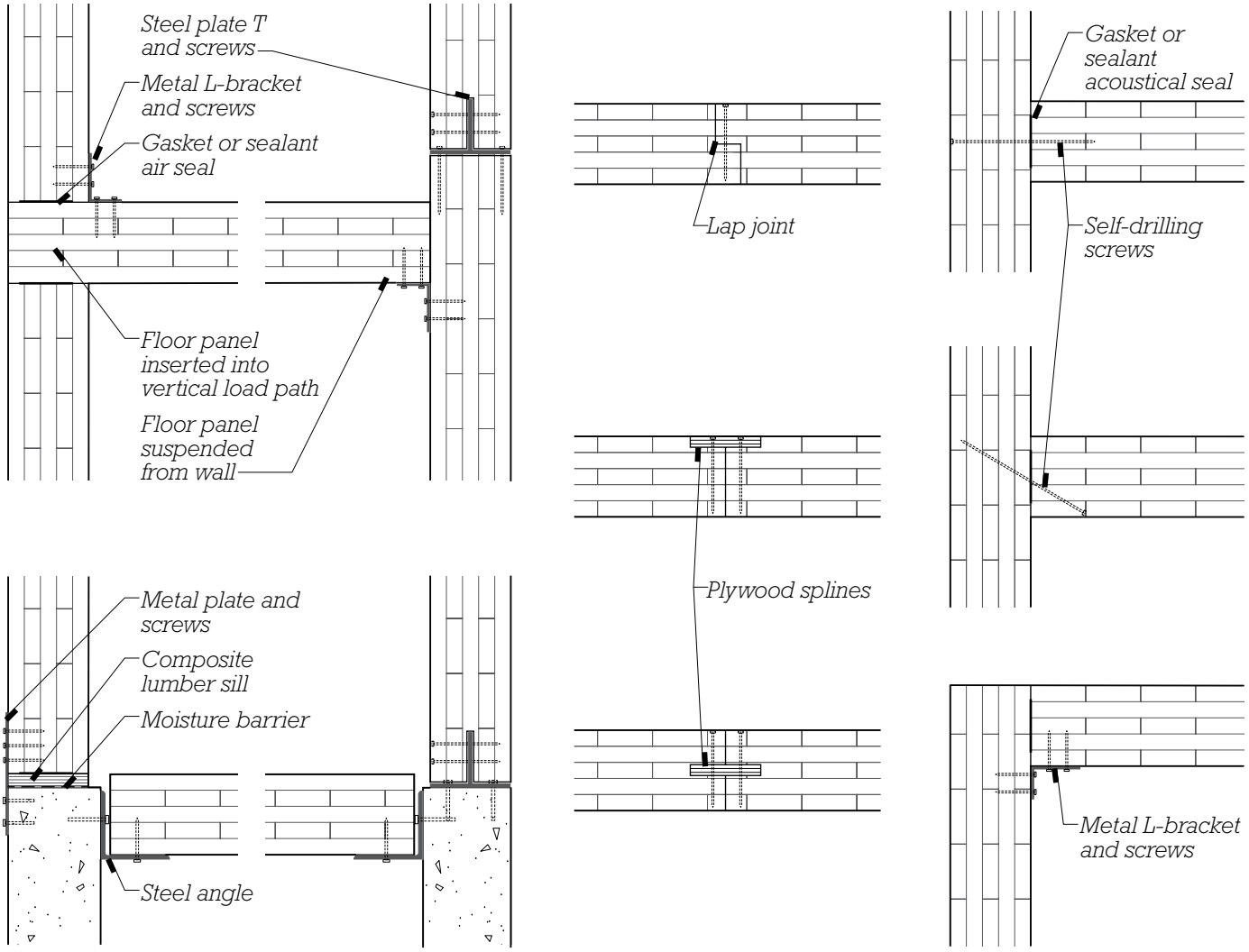


FIGURE 4.28

CLT connection details from Figure 4.27. In (*A*), two strategies are illustrated for wall-to-floor panel connections. When floor panels are inserted into the vertical load path of the wall panels (*left*), shrinkage in the floor panels accumulates from floor to floor. This approach is only suitable for low-rise buildings. For taller buildings, floor panels should be suspended from the sides of walls (*right*), so that shrinkage in floor panels is isolated from the building structure.

In the completed building, the cross-laminated timber structure must be protected from the weather, insulated, and finished on the interior. Exterior cladding, thermal insulation, and air and water-resistive barrier membranes are applied to the outside of exterior panels, thereby keeping the panels within the heated and dry interior environment (Figure 4.29*A*).

On the interior, panels may be left exposed. Or, they may be covered with gypsum wallboard where required for protection from fire or where a finish other than the raw panel surface is preferred. Furred or suspended finishes can be used to provide concealed space for acoustic insulation, wiring, plumbing, ductwork, and other building services. However, like Type IV-HT construction, concealed combustible spaces are not permitted. Gypsum underlayment or concrete topping slabs applied over floor panels provide fire resistance and improve acoustical separation between floors (Figure 4.29*B*,*C*).

Approaches to using other large format wood panels, such as nail-laminated timbers and dowel-laminated timbers, are similar to those for CLTs. These other panel types are mostly limited to use as floor decking in mass timber construction at this time.

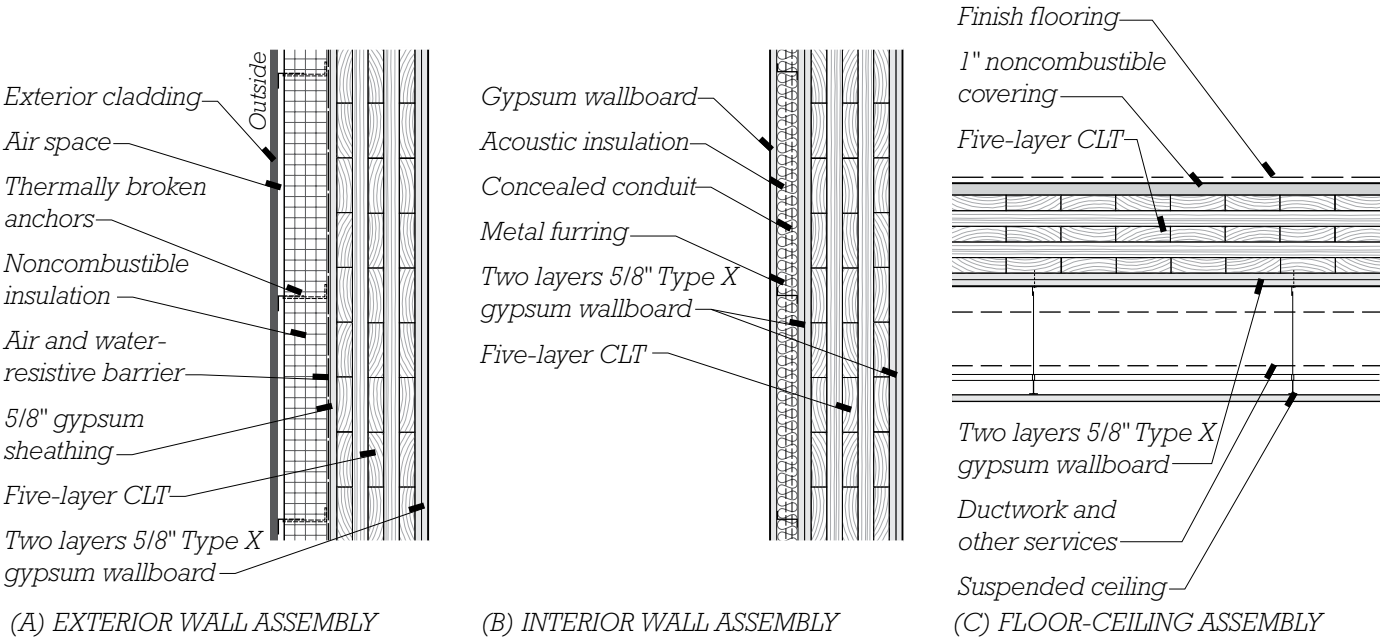


FIGURE 4.29

Examples of CLT wall and floor assemblies with approximately 2-hour fire resistance ratings. In each, two layers of gypsum wallboard provide 80 minutes of fire protection and then 40 minutes or more are provided by charring of the wood panel. In (*A*), the exterior cladding and insulation materials must be noncombustible. (Walls taller than 40 feet (12 m) must pass additional fire testing that might dictate changes from what is shown here or preclude wood panels entirely.) In (*B*), both sides of the panel are protected by two layers of gypsum wallboard. On one side, metal furring and an additional finish layer create a cavity for acoustic insulation and the hiding of electrical conduit or other services. In (*C*), the top surface of the CLT is covered with at least 1 inch (25 mm) of noncombustible material, such as a gypsum underlayment or concrete topping. The underside of the panel is protected with two layers of gypsum wallboard. A suspended ceiling provides concealed space for lighting, ductwork, and other services.

Fire-Resistance Rated Connections

Where mass timber or heavy timber frame members must meet fire resistance rating requirements, the connections supporting these elements must meet the same ratings. This is achieved by embedding the metal components within the wood member (for example, as occurs with a knife plate connection) or covering connections with gypsum wallboard or other fire-protective material.

Lateral Stability

As with any structural system, as the height of a mass timber building increases, resisting the forces of wind and earthquake becomes an increasingly difficult challenge. Shear walls composed of cross-laminated timber panels are one way to provide lateral force resistance in mass timber structures. However, while CLT panels are strong and stiff, they lack ductility and, when stressed beyond their capacity, fail suddenly. When relied on for lateral force resistance (and especially, for resistance to seismic forces), either panel strength must be overdesigned to compensate for this brittle behavior or ductility must be introduced through the connections between panels. With the latter approach, when such walls are subjected to lateral forces, the panels themselves remain square and rock slightly as the connectors flex, a behavior called "rocking walls."

At this time, CLT shear walls are considered feasible for lateral force resisting systems in mass timber structures as high as approximately 8 to 12 stories. At greater heights, braced structural steel framing or concrete shear walls are more suitable (Figure 4.30). Research and development of mass timber lateral force resisting systems is still in early stages, and the capabilities of such systems will continue to evolve.

Protecting Mass Timber Structures during Construction

During the construction of mass timber buildings, large volumes of wood are temporarily exposed to the exterior elements. If these components are not adequately protected, they can absorb significant amounts of unwanted moisture. This, in turn, can lead to deterioration of the wood, as well as large dimensional changes

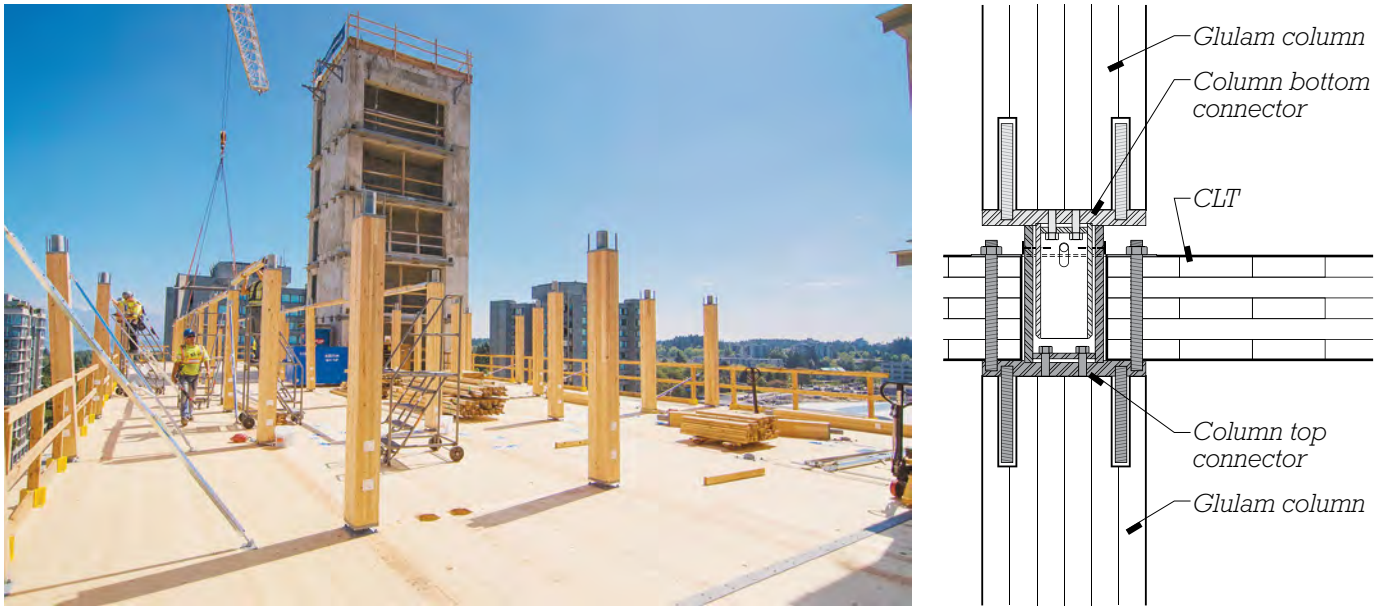


Figure 4.30
Brock Commons, Vancouver, BC, by Action Ostry Architects, Fast + Epp Structural Engineers, and mass timber installers Seagate Structures. *Left:* The structure consists of glulam and PSL columns, CLT floors, a ground level concrete podium, and a pair of concrete cores providing lateral stability. At 18 stories and 174 feet (53 m) tall, this was, at the time of its completion, the world's tallest mass timber building. *Right:* Columns arrive on site with connectors preinstalled. The bottom connector (lighter tone) slides into the top connector (darker tone) and is then fixed in place. *(Photo by Pollux Chung, courtesy of Seagate Structures. Detail adapted from F+E.)*

after the building is enclosed and wood members return to a dry state. Measures used to protect wood members may include:

- Application of water-repellent coatings to wood components
- Covering of wood components during transportation to the building site
- Scheduling construction to occur during dry seasons of the year
- Applying a concrete topping or other protective covering to floors as early as possible
- Temporarily tenting the building structure
- Rapid and early installation of exterior wall systems

Fire safety during the construction of mass timber buildings also requires special consideration, since protective measures that will be part of the completed building, such as fire-resistant protection of wood members or building sprinkler systems, are not yet fully in place. To minimize fire risk, special work procedures, such as limiting the use of open-flame devices, are implemented, and installation of fire-protective coverings are required to proceed no more than a prescribed number of floors behind the erection of the mass timber elements.

Wood–Concrete Composite Construction

Heavy timber beams and cross-laminated timber panels can be combined with cast-in-place concrete to create floor systems in which the wood and concrete act together as unified structural components with greater structural efficiency.

In wood–concrete composite systems, rows of *shear connectors* are installed into the upper face of the heavy timber beams or CLT panels. These connectors may be heavy lag screws that are closely spaced, continuous angles made of perforated metal, or other components that will bridge between the wood and concrete and mechanically engage with both materials. The shear connectors are installed so that they project 1 to 2 inches (25 to 50 mm) above the wood surface. Concrete is cast on top of the panels or over the beams, fully covering the connectors. Once the concrete has cured, the shear connectors engage with both the wood and the concrete so that under structural loading these components share stresses and deflect together as one element. This more efficient structural configuration can span further or carry greater loads in comparison to the same structural components acting without composite action. (For a further explanation of composite structural members, see the subsection "Composite Beam Construction" in Chapter 11.)

Longer Spans in Heavy Timber and Mass Timber

Large Beams

Very large wood beams are usually built up of wood laminations or strands. Such beams are stronger and more dimensionally stable than sawn wood beams and can be made in the exact size and shape desired (Figure 4.31).

Rigid Frames

The cruck (Figure 4.1), cut from a bent tree, was a form of *rigid frame*. Today's rigid frames are glue-laminated to shape and find wide use in longer-span buildings. Standard configurations are readily available (Figure 4.32), or the designer may order a custom shape. Rigid frames exert a horizontal thrust, so they must be tied together at the base with *steel tension rods*, also called *tie rods*. In laminated wood construction, rigid frames are often called *arches*, acknowledging that the two structural forms act in a very similar manner.

Figure 4.31
Installing tongue-and-groove roof decking over laminated beams and girders. *(Courtesy of American Institute of Timber Construction.)*

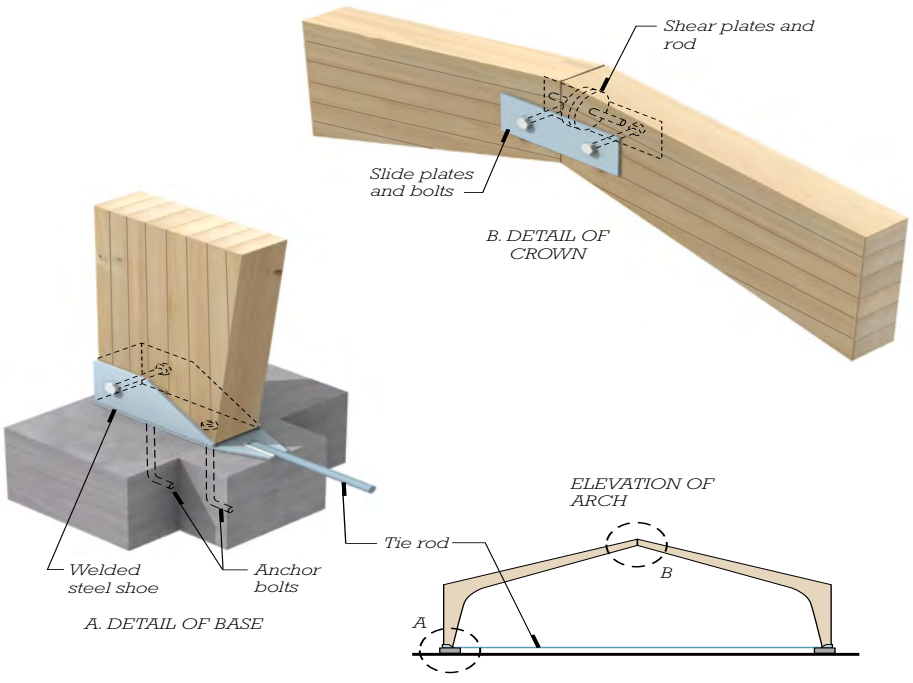


Figure 4.32
Typical details for three-hinged arches of laminated wood. The tie rod is later covered by the floor slab. The shear plate in the crown connection is similar to a split-ring connector (see Chapter 3) and serves to spread forces in the connection across a larger surface area of wood.

Trusses

The majority of wood trusses built each year are light roof trusses of nominal 2-inch (38-mm) lumber joined by toothed plates. For larger buildings, however, *heavy timber trusses* may be used. Their joints are made with steel bolts or pins and welded steel plate connectors, split-ring connectors, or other proprietary connection hardware. Sawn, laminated, and structural composite timbers may be used, sometimes in combination with steel members. Many shapes of truss are possible, and spans of more than 100 feet (30 m) are easily achieved (Figures 4.33 and 4.34).

FIGURE 4.33
A contemporary heavy timber truss made from solid wood members. At the truss peak, connections rely on knife plates and through-bolts. At the foot of the truss, a steel shoe anchors the truss to the supporting beam. *(Photo by Joseph Iano.)*

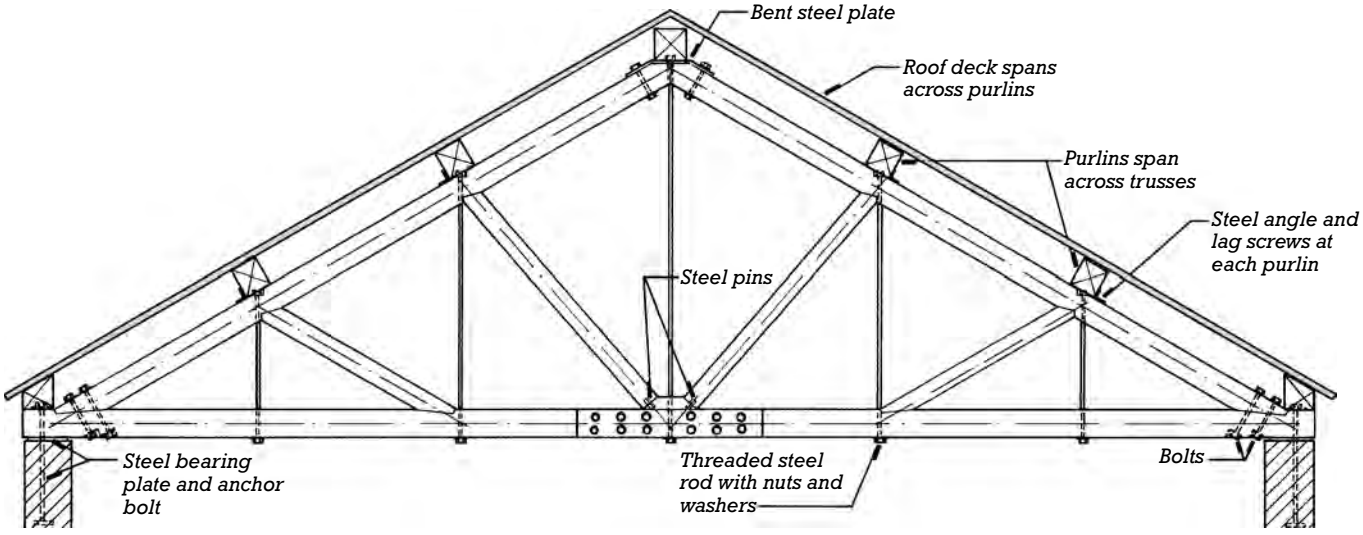


FIGURE 4.34
A traditional heavy timber roof truss with steel rod tension members. This type of truss is easy to construct but cannot be used if wind uplift forces are so strong as to cause the forces in the tension members to reverse (such slender steel rods cannot resist compressive forces). The center splice in the lower chord of the truss is required only if it is impossible to obtain single pieces of lumber long enough to reach from one end of the truss to the other.

Arches and Domes

Traditionally, long curved timbers for making *heavy timber vaults* or *arches* and *heavy timber domes* have been fabricated from glue-laminated wood (Figures 4.35 and 4.36). More recently other structural wood composite types can also be used to make similar long-span members (Figure 4.37). These shapes are widely used in athletic arenas, auditoriums, warehouses, and factories. Like rigid frames, arched and domed structures exert lateral thrusts that must be countered by tie rods or suitably designed foundations.

FIGURE 4.35
Semicircular laminated wood arches support the timber roof of Back Bay Station in Boston. Notice the use of horizontal steel tie rods to resist the thrust of the arches at the base. *(Architect: Kallmann McKinnell & Wood. Photo © Steve Rosenthal.)*

FIGURE 4.36
This laminated wood dome spans 530 feet (161.5 m) to cover a 25,000-seat stadium and convention center in Tacoma, Washington. *(Architect: McGranahan Messenger & Associates. Structural engineer: Chalker Engineers, Inc. Photo by Gary Vannest, courtesy of American Wood Council.)*

FIGURE 4.37
Metropol Parasol, Plaza de la Encarnacion, Seville, Spain, by J. Mayer H. Architects and ARUP engineers. This laminated veneer lumber structure covers 490 feet × 245 feet of area and is close to 100 feet tall (150 × 75 × 30 m). It shades the public square and supports a high-level café and panoramic walkway. The LVL members are joined with a steel rod and epoxy connector developed specifically for this structure. The largest single wood member measures 54 feet × 11 feet × 6 inches (16.5 × 3.5 × 0.14 m). *(Photo by Jan-Peter Koppitz.)*

Preliminary Design of Heavy Timber and Mass Timber Structures

- Estimate the nominal depth of **wood roof decking** at 1/45 of its span. Estimate the depth of **wood floor decking** at 1/35 of its span. Standard nominal depths of wood decking are 2, 3, 4, 6, and 8 inches (actual size 38, 64, 89, 140, and 184 mm).
- Where fire-resistance is not required, lightly loaded **cross-laminated timber wall panels** may be three laminations, approximately 4 inches (100 mm) in total thickness. Where a fire-resistance rating is required, or for heavier loads, panels should be at least five laminations, not less than approximately 7 inches (175 mm) in thickness.
- For **cross-laminated floor and roof decks**, use the same lamination minimums noted for CLT wall panels, and estimate the depth at not less than 1/40 of the span for light loads or 1/30 of the span for medium to heavy loads.
- Estimate the depth of **solid wood beams** at 1/15 of their span and the depth of **glue-laminated beams** at 1/20 of their span. Add a nominal 6 inches (150 mm) to these depths for girders. The width of a solid wood beam or girder is usually 1/4 to 1/2 of its depth. The width of a glue-laminated beam typically ranges from 1/7 to 1/4 of its depth.
- Estimate the depth of timber **triangular roof trusses** at 1/5 to 1/2 of their span and the depth of **bowstring trusses** at 1/2 to 2/3 of their span.
- To estimate the size of a **wood column**, add up the total roof and floor area supported by the column. A nominal 6-inch (actual size 140 mm) column can support up to about 400 square feet (37 m^2) of area, an 8-inch (actual size 184 mm) column 1000 square feet (93 m^2), a 10-inch (actual size 235 mm) column 1500 square feet (140 m^2), a 12-inch (actual size 286 mm) column 2500 square feet (230 m^2), and a 14-inch (actual size 337 mm) column 3500 square feet (325 m^2). Wood columns are usually square or nearly square in proportion.

For actual sizes of solid timbers, see Figures 3.21 and 3.22. Standard sizes of glue-laminated timbers are given in subsection "Glue-Laminated Wood" in Chapter 3. For a building that must qualify as Type IV Heavy Timber construction under the IBC, minimum timber sizes are given in Figure 4.5.

These approximations are valid only for purposes of preliminary building layout and must not be used to select final member sizes. They apply to the normal range of building occupancies, such as residential, office, commercial, and institutional buildings.

For more comprehensive information on preliminary selection and layout of a structural system and sizing of structural members, see Edward Allen and Joseph Iano, *The Architect's Studio Companion* (6th ed.), Hoboken, NJ, John Wiley & Sons, 2017.

MasterFormat Sections for Heavy Timber and Mass Timber Construction

06 13 00	**HEAVY TIMBER CONSTRUCTION**
06 13 23	Heavy Timber Framing
06 13 26	Heavy Timber Trusses
06 15 00	**WOOD DECKING**
06 15 19	Timber Decking
06 15 23	Laminated Wood Decking

Key Terms

cruck
heavy timber frame
mass timber
Type IV-HT (Heavy Timber) construction
char
encapsulation
effective char rate
Mill construction
firecut
bearing block
knife plate
fireblocking
shear connector
rigid frame
steel tension rod, tie rod
arch
heavy timber truss
heavy timber vault, heavy timber arch
heavy timber dome

Review Questions

1. What are the two basic requirements for Type IV Heavy Timber construction in the International Building Code?

2. How do the requirements for resistance to fire differ between Type IV Heavy Timber and the proposed new construction types for taller mass timber buildings?

3. Explain the difference between char and encapsulated fire protection of wood members.

4. What are three important principals in the design of heavy timber connections?

5. Assume that heavy timber beams will shrink approximately 2 percent in the cross-grain dimension as they continue to dry after installation in a building. If there are four framed floor levels, supported by 24-inch-deep (600 mm) beams at each level, what would be the accumulated shrinkage at the roof if columns at each floor rested on these beams, rather than being supported as recommended in this chapter?

6. Draw from memory one or two typical details for the intersection of a wood column with a floor of a building of Heavy Timber construction.

7. Draw from memory a typical exterior CLT wall section. Label each component.

Exercises

1. Determine from Figures 1.4 and 4.7 whether a building you are currently designing could be built of Type IV Heavy Timber or one of the new proposed construction types for taller mass timber buildings. If not, what modifications can you make in your design so that it will conform to the requirements for one of these types?

2. Find a barn or mill that was constructed in the 18th or 19th century and sketch some typical connection details. How is the structure stabilized against wind and other lateral forces?

3. Obtain a book on traditional Japanese construction from the library and compare Japanese timber joint details with 18th- or 19th-century American practice.

Selected References

American Institute of Timber Construction. *Timber Construction Manual* (6th ed.). Hoboken, NJ, John Wiley & Sons, 2012.

This is a comprehensive design handbook for timber structures, including detailed engineering procedures as well as general information on wood and its fasteners.

APA—The Engineered Wood Association. *Glulam Connection Details* (Technical Note; Form No. EWS T300H). Tacoma, WA, 2007.

This 21-page reference contains dozens of examples of how to, and how not to, detail connections in heavy timber buildings. Available as free download from www.apawood.org.

American Wood Council. *Calculating the Fire Resistance of Exposed Wood Members* (Technical Report No. 10). Leesburg, VA, 2016.

Though highly technical in part, this reference also provides a comprehensive discussion of the concepts and historical background of fire design for wood members and their connections. Available as a free download from www.awc.org.

American Wood Council and International Code Council. *Code Conforming Wood Design*. Leesburg, VA, updated regularly.

The comprehensive reference provides guidance on the code-compliant design of wood structures of all sizes and types and is updated triennially with each new major edition of the International Building Code. Available as a free download from www.awc.org.

Chappell, Steve. *A Timber Framing Workshop: Joinery, Design & Construction of Traditional Timber Frames*. Brownfield, ME, Fox Maple Press, 2011.

A guide to the design and construction of heavy timber frame structures.

Kaufmann, Hermann, et.al. *Manual of Multi-Storey Timber Construction*. Munich, Detail Business Information, GmBH, 2018.

This reference provides a comprehensive discussion of tall wood building systems, environmental impacts, and techniques.

MGA | Michael Green Architecture. *The Case for Tall Wood Buildings* (2nd ed.). Vancouver, BC, 2018.

This reference provides a broad coverage of the ecological and economic cases for mass timber construction, performance criteria, comparison of protype designs, and examples of details.

Websites

American Institute of Timber Construction: aitc-glulam.org

American Wood Council, Tall Mass Timber: www.awc.org/tallmasstimber

Canadian Wood Council: www.cwc.ca

Structurlam Intelligence in Wood: www.structurlam.com

Tallwood Design Institute: http://tallwoodinstitute.org/

ThinkWood, Taller Buildings: www.thinkwood.com/building-better/taller-buildings

Timber Framers Guild: www.tfguild.org

5

Wood Light Frame Construction

- History
- Platform Frame

Sustainability and Wood Light Frame Construction

- Foundations for Wood Light Frame Structures
  - Other Foundation Materials
- Building the Frame
  - Planning the Frame
  - Erecting the Frame
  - Attaching the Frame to the Foundation
  - Floor Framing
  - Wall Framing
  - Lateral Force Resistance and Shear Walls
  - Upper-Level Floor and Wall Framing
  - Roof Framing
- Variations on Wood Light Frame Construction
  - Framing for Increased Thermal Efficiency
  - Framing for Optimal Lumber Usage
  - Prefabricated Framing Assemblies

Preliminary Design of Wood Light Frame Structures

- Wood Light Frame Construction and the Building Codes
- Uniqueness of Wood Light Frame Construction

A New England school of arts and crafts is housed in a cluster of small buildings of wood light frame construction that cling to a dramatic mountainside site overlooking the ocean. *(Architect: Edward Larrabee Barnes. Photo by Joseph W. Molitor.)*

Wood light frame construction is the most versatile of all building systems. There is scarcely a shape it cannot be used to construct, from a plain rectangular box to cylindrical towers to complex foldings and shapes of every description. During the century and a half since it first came into use, wood light framing has served to construct buildings ranging from reinterpretations of nearly all the historical styles to uncompromising expressions of every contemporary architectural philosophy. During this same period, it has assimilated without difficulty a bewildering and unforeseen succession of technical improvements in building: central heating, air conditioning, gas lighting, electricity, thermal insulation, indoor plumbing, prefabricated components, and communications cabling.

Light frame buildings are easily and swiftly constructed with a minimal investment in tools. Many observers of the building industry have criticized the supposed inefficiency of light frame construction, which is carried out largely by hand methods on the building site, yet it has successfully fought off competition from industrialized building systems of every sort, partly by incorporating their best features, to remain the least expensive form of durable construction. It is the common currency of small residential and commercial buildings in North America today.

Wood light frame construction has its deficiencies: If ignited, it burns rapidly; if exposed to dampness, it decays. It expands and contracts by significant amounts in response to changes in humidity, sometimes causing chronic difficulties with cracking plaster, sticking doors, and buckling floors. The framing itself is so unattractive that it is seldom left exposed in a building. These problems can be mitigated, however, by clever design and careful workmanship, and there is no arguing with success: Frames made by the monotonous repetition of wooden joists, studs, and rafters are likely to remain the primary system of building in North America for a long time to come.

FIGURE 5.1
A wood light frame single-family home under construction. At bottom right is a concrete slab on grade garage floor. At the left, concrete basement walls have been covered with a dimpled plastic drainage mat. Exterior walls are framed with solid lumber 2 × 6 studs sheathed with OSB panels. Floors are framed with I-joists (and OSB subflooring not visible in this photograph). On top of the upper story walls, prefabricated roof trusses have been stacked in preparation for their installation. *(Photo by Joseph Iano.)*

History

Wood light frame construction was the first uniquely American building system (Figure 5.1). It was developed in the first half of the 19th century when builders recognized that the closely spaced vertical members used to infill the walls of a heavy timber building frame were themselves sufficiently strong that the heavy posts of the frame could be eliminated. Its development was accelerated by two technological breakthroughs of the period: Boards and small framing members of wood had recently become inexpensive for the first time in history because of the advent of the water-powered sawmill, and machine-made nails had become remarkably cheap compared to the hand-forged nails that preceded them.

The *balloon frame* was the earliest wood framing system to be constructed exclusively of slender, closely spaced wooden members: *joists* for the floors, *studs* for the walls, *rafters* for the sloping roofs. Heavy posts and beams were completely eliminated, and with them, the difficult, expensive mortise-and-tenon joinery they required. There was no structural member in a frame that could not be handled easily by one or two carpenters, and each of the hundreds of joints was made with lightning rapidity with two or three nails. The impact of this new building system was revolutionary: In 1865, G. E. Woodward could write in *Woodward's Country Homes* that "[a] man and a boy can now attain the same results, with ease, that twenty men could on an old-fashioned frame. . . . [T]he Balloon Frame can be put up for forty percent less money than the mortise and tenon frame."

The balloon frame (Figure 5.2, *right*) used full-length studs that ran continuously for two stories from foundation to roof. In time, it became apparent that these were too long to erect efficiently. Furthermore, the tall, hollow spaces between studs acted as multiple chimneys in a fire, spreading

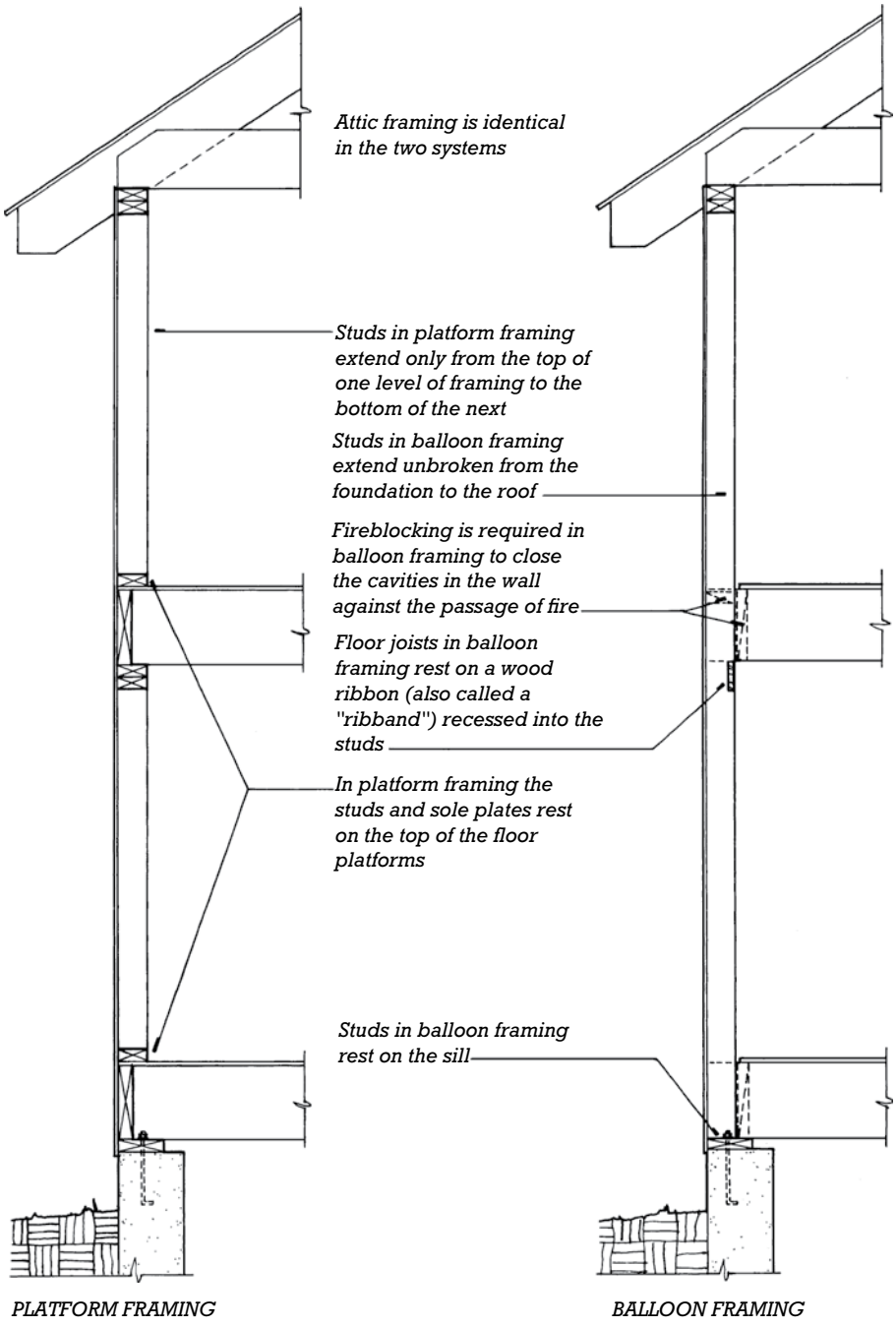
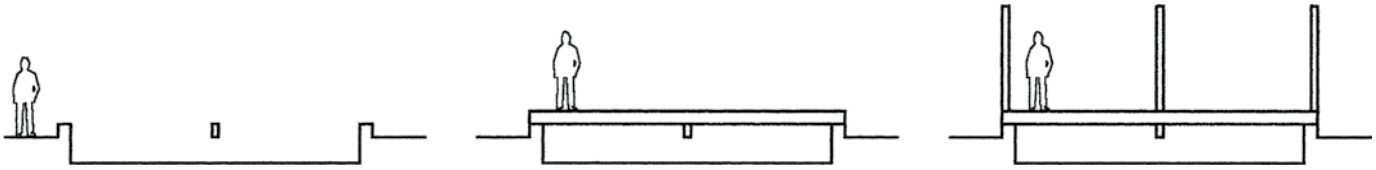


Figure 5.2
Comparative framing details for platform framing (*left*) and balloon framing (*right*). Platform framing is much easier to erect and is the only light framing system used today. However, a platform frame settles considerably as the wood dries and shrinks. If nominal 12-inch (286-mm) joists are used to frame the floors in these examples, the total amount of loadbearing cross-grain wood between the foundation and the attic joists is 33 inches (838 mm) for the platform frame and only 4½ inches (114 mm) for the balloon frame.

Interactive Exercise



the blaze rapidly to the upper floors, unless they were closed off with wood or brick *fireblocking* at each floor line. Several modified versions of the balloon frame were subsequently developed in an attempt to overcome these difficulties. The final, most successful of these, the *platform frame* (Figure 5.2, *left*), is now the universal standard for wood light frame construction.

Platform Frame

Although sometimes complex in its details, the platform frame is simple in concept (Figure 5.3). A floor platform is built. Loadbearing walls are erected upon it. A second-floor platform is built upon these walls and a second set of walls upon this platform. The attic and roof are then built upon the second set of walls. There are, of course, many variations: A concrete slab that lies directly on the ground is sometimes substituted for the ground-floor platform; a building may be only one story tall, or three or more stories in height; and roofs of various types are possible. The essentials, however, remain: A floor platform is completed at each level, and the walls bear upon that platform rather than directly upon the walls of the story below.

The advantages of the platform frame over the balloon frame are several: It uses short, easily handled lengths of lumber for the wall framing. Fireblocking is naturally provided by the platform construction at each floor level. Its platforms are convenient working surfaces for the carpenters who build the frame. The major disadvantage of the platform frame is that each platform constitutes a thick layer of wood whose grain runs horizontally. This leads inevitably to a relatively large amount of vertical shrinkage in the frame as excess moisture dries from the wood, which, if not properly accounted for, can cause distress in the exterior and interior finish surfaces.

A conventional platform frame is made entirely of nominal 2-inch members, which are actually 1½ inches (38 mm) in thickness. These may be ordered and delivered cut to the nearest 2-foot (600-mm) length, then measured and sawn to exact length on the building site. In larger-volume work, wall studs are frequently precut to the precise required length at the lumberyard and delivered to the site ready to install. Connections are made with nails, alone or in combination with metal connectors as required by the characteristics of each joint. Nails are driven either by hammer or, more frequently, nail gun. In either case, connections are quickly made because the nails are installed without drilling holes or other time-consuming joint preparation.

Each plane of structure in a platform frame is made by aligning pieces of framing lumber parallel to one another at specified intervals, nailing these to crosspieces at either end to maintain their spacing and flatness, and then covering the plane of framing with *sheathing*, a facing layer of boards or panels that join and stabilize the pieces into a single structural unit, ready for the application of finish materials inside and out (Figure 5.4). In the floor structure, the parallel pieces are the floor joists, and the crosspieces at the ends of the joists are called *rim boards*, or *band joists*. The sheathing applied over the floor framing is called the *subfloor*. In a wall structure, the parallel pieces are the studs, the crosspiece at the bottom of the wall is the *sole plate*, or *bottom plate*, and the crosspiece at the top (which is frequently doubled for strength) is called the *top plate*. In a sloping roof, the wall top plates play the role of the lower crosspiece and a *ridge board* is provided at the roof peak.

Openings are required in all these planes of structure, such as for windows and doors in the walls, stairs and chimneys in the floors, and chimneys, skylights, and dormers in the roofs. In each case, additional framing is required to support the ends of the shortened framing members. Openings in floors and roofs are framed with *headers* and *trimmers* (see Figure 5.15). For large openings, these members are doubled, to account for the higher loads they carry. In walls, *sills* head off the bottoms of window and door openings, while *trimmer studs* on the sides provide support to loadbearing headers across the tops (see Figure 5.32).

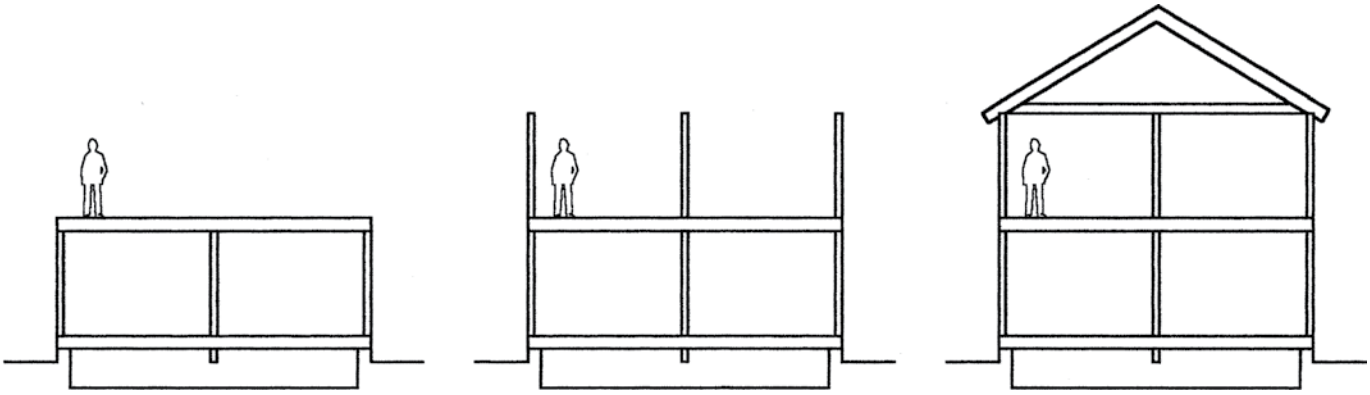


FIGURE 5.3
The concept of platform framing, shown in cross section, reading from left to right: A foundation wall is constructed. A ground-floor platform is framed and sheathed. Ground-floor wall frames are assembled horizontally on the platform, then tilted into their final positions. A second-floor platform is constructed on top of the ground-floor walls, and the process of wall construction is repeated. The attic floor and roof are added.

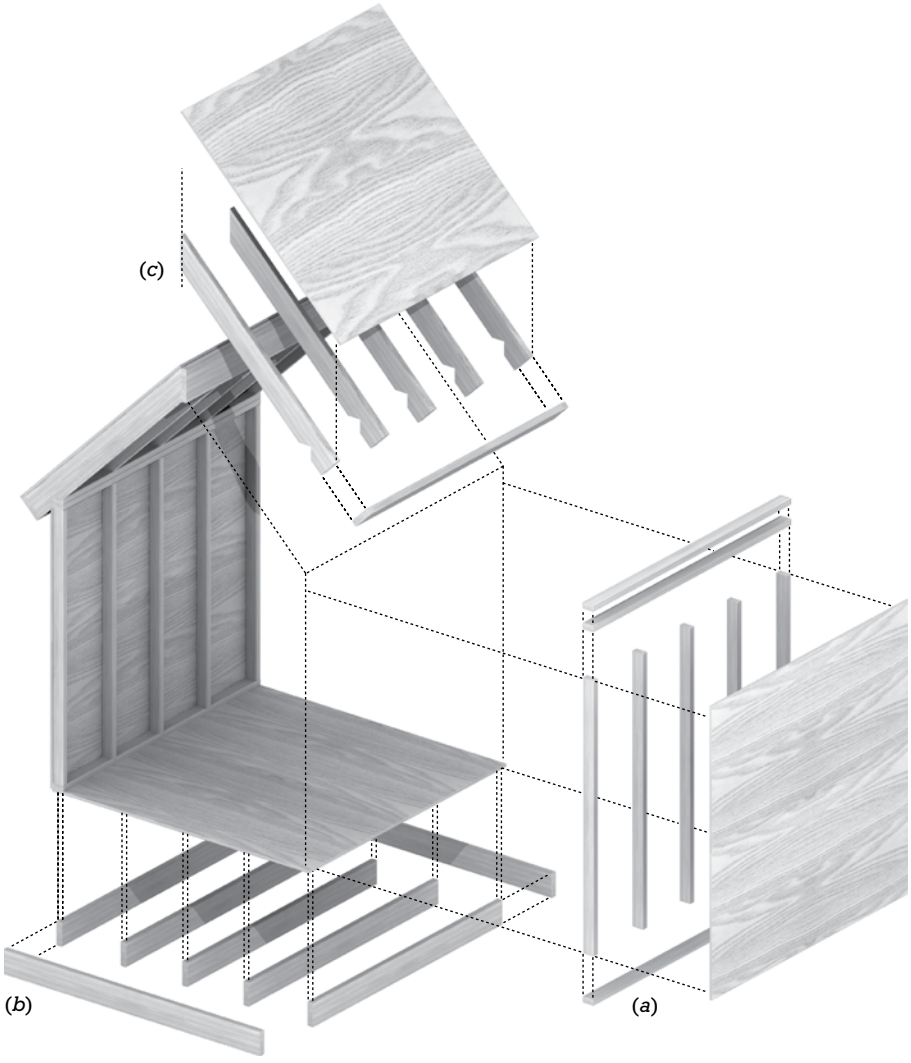


FIGURE 5.4
The basic components of platform frame construction. (*a*) Walls are framed with repetitive vertical studs, connected top and bottom by horizontal plates. (*b*) Floors are framed with repetitive joists connected at their ends by rim boards or band joists. (*c*) Sloped roofs are framed with rafters, with a ridge board at the peak. Every surface is sheathed, mostly commonly with plywood or OSB panels.

Interactive Exercise

Sustainability and Wood Light Frame Construction

In addition to the considerations of sustainability and wood discussed in Chapter 3, the following pertain particularly to wood light frame construction:

Building and Material Life-Cycle Impacts

- One life-cycle analysis of residential construction methods found that, in comparison to homes built of wood, those built of steel or concrete consumed 12 to 20 percent more energy and contributed 15 to 29 percent more to global warming, respectively. Homes constructed of wood also compared favorably in other environmental measures, such as air pollution, water pollution, resource use, and waste generation. This study considered both construction and operation over a 20-year period, but did not consider the effects of wood carbon sequestration or end-of-life effects.
- A wood light frame building can be designed to minimize waste in various ways. It can be dimensioned to utilize, as much as possible, full sheets and lengths of wood products. Advanced framing techniques, discussed separately in this chapter, can be employed to reduce the amount of material needed to construct a wood light frame structure.
- Panelized and modular construction systems encourage efficient use of materials and reductions in construction waste.

Throughout the platform frame, the floor joists, wall studs, and roof rafters are consistently arranged so these members fall on a 4-foot (1220-mm) module. This ensures that standard 4-foot × 8-foot (1220-mm × 2440-mm) panels used to cover the inner and outer faces of the framing are readily supported at their ends (see, for example, Figure 5.17). Most commonly, framing members are spaced at 16 inches or 24 inches (406 or 610 mm) o.c.; *o.c.* or *on center* meaning that the spacing is measured from center to center of the members.

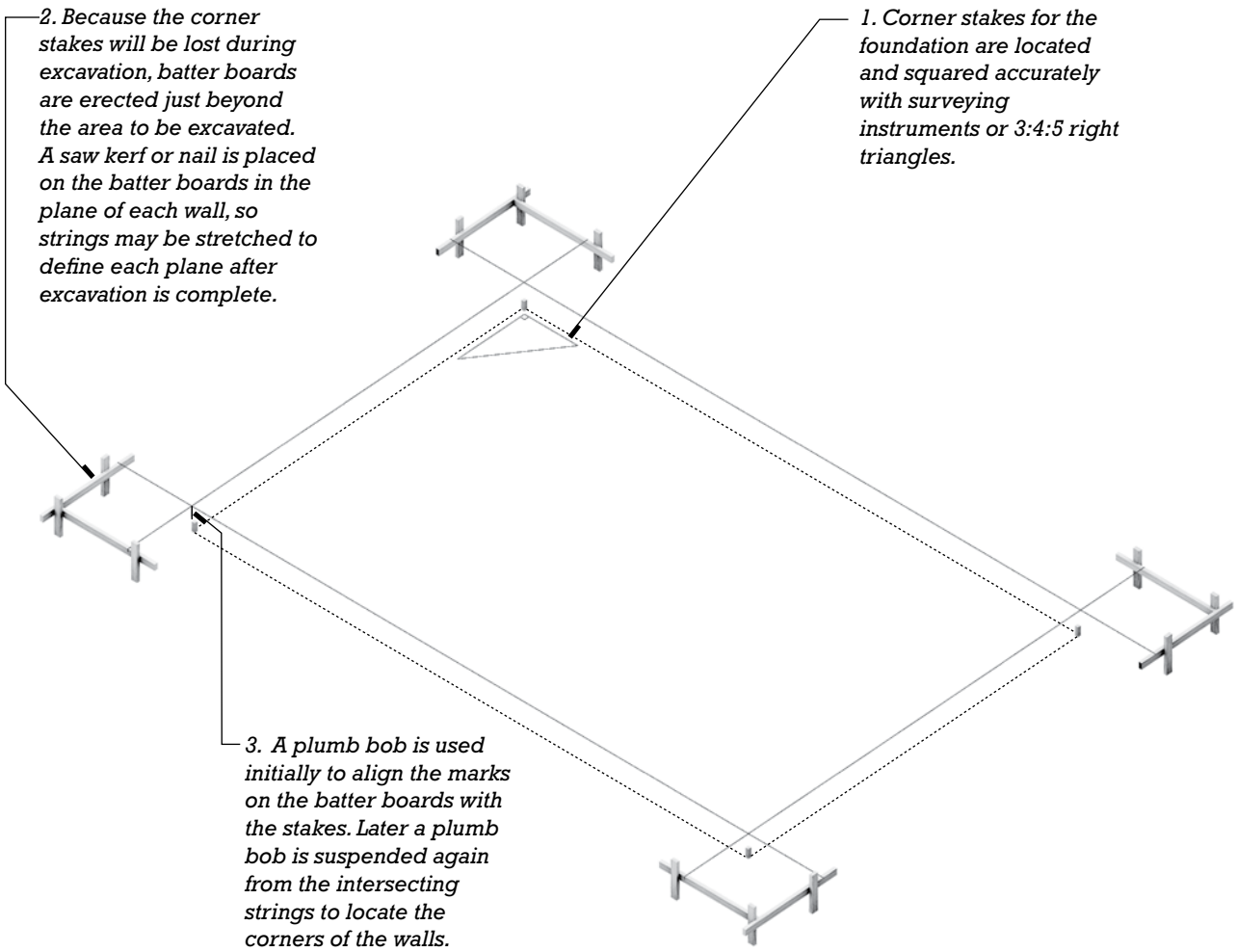
The sheathing, usually plywood or oriented strand board (OSB) nailed over the outside face of the framing, is a key component, tying the various parts of the frame into a structural whole. In the wall frame, for example, the end-nailed connections between top or bottom plates and the studs, by themselves, offer little resistance to wind uplift forces acting on the roof. It is the wall sheathing spanning across these parts that provides the structural continuity needed to carry these forces from the roof to the foundation. Similarly, subflooring and roof sheathing provide important structural continuity to these parts of the structure. As discussed later in this chapter, structural sheathing plays a critical role in the platform frame's resistance to lateral forces exerted by wind or earthquake. Sheathing also furnishes a surface to which shingles, boards, and flooring are nailed for finish surfaces.

Foundations for Wood Light Frame Structures

Most residential and small commercial wood light frame buildings are built on shallow foundations consisting of spread footings, basement or crawlspace walls, or slabs on grade. Once these would have been constructed of stone or brick; today stronger, more durable, and more easily waterproofed steel-reinforced sitecast concrete and concrete masonry are the materials of choice. Examples of these foundation types are illustrated and explained in more detail in Figures 5.5 through 5.12. For larger buildings (for example, multistory apartments), or where soil conditions close to the surface are problematic, deeper foundation types, as discussed in Chapter 2, may also be used.

For simple basements and crawlspaces, protection from water entry usually takes the form of bituminous or cement plaster dampproofing applied to the outside of the foundation walls, along with drainage materials surrounding the basement walls and perimeter footing drains to draw water away (Figures 5.6 through 5.8). Where groundwater conditions are severe or there is a need to keep the basement interior as dry as possible, more expensive and resistant waterproofing treatments may take the place of dampproofing. Slabs on grade should be protected from moisture in the ground below by a heavy plastic sheet vapor retarder. In areas where radon soil gas is a concern, measures for protecting against the entry of this gas into the structure (also as discussed in Chapter 2) may be part of the foundation construction as well.

The construction of a platform frame building begins with the driving of stakes to fix its position on the site, and the placing of batter boards as reference marks for the builder.



1

FIGURE 5.5

Step one in the construction of a simple platform frame building: establishing the location of the building on the site. After the corners of the foundation have been staked, *batter boards* are erected safely beyond the limits of the excavation area. String lines crossing over the corner stakes are stretched from the batter boards, and their positions on the boards are preserved with notches or nails in the boards. Later, after excavation, the strings are stretched again, and the foundation corners can be relocated at the bottom of the excavation. This figure begins a series of isometric drawings that will follow the erection of a wood light frame building step-by-step throughout the course of this chapter.

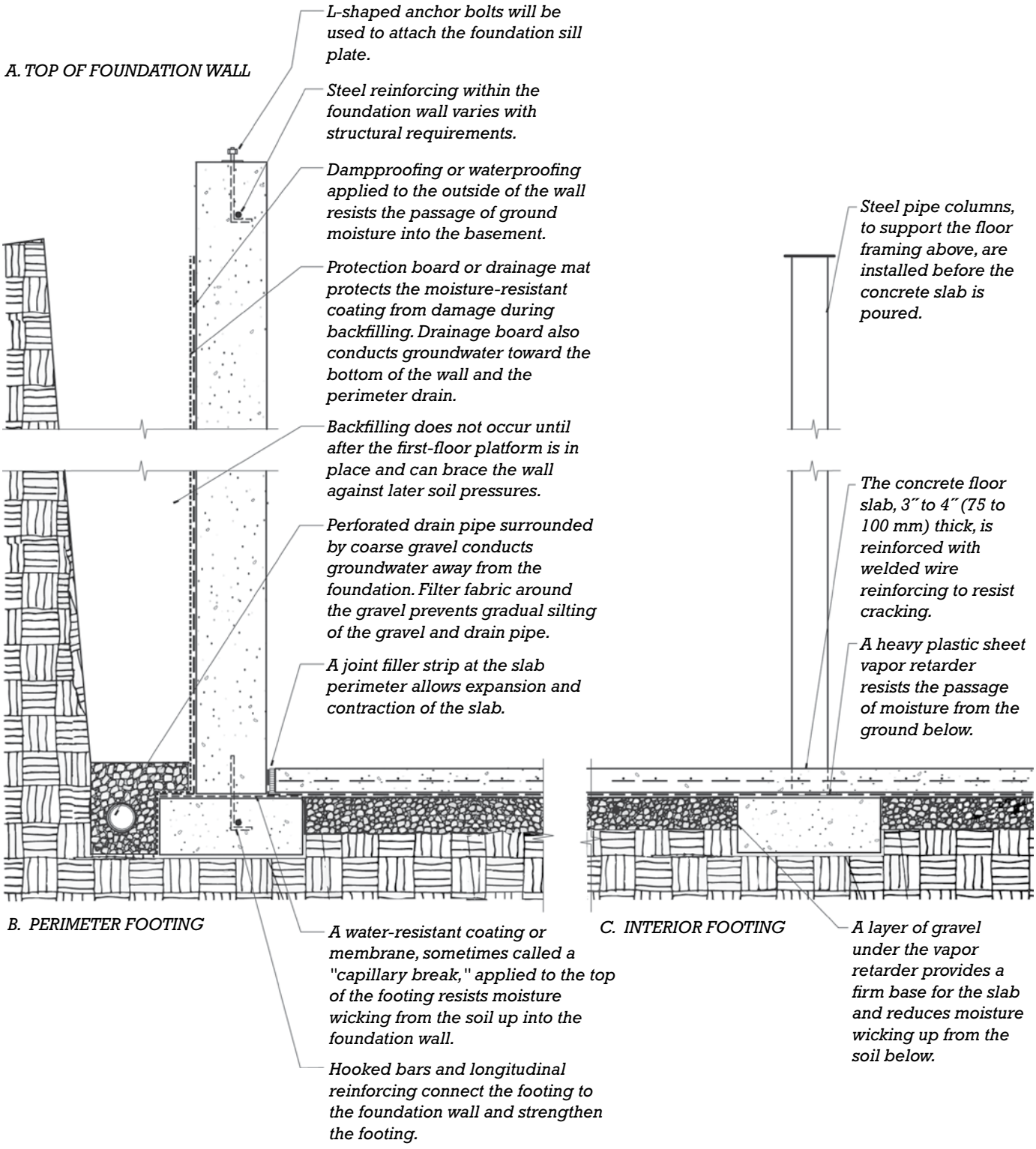
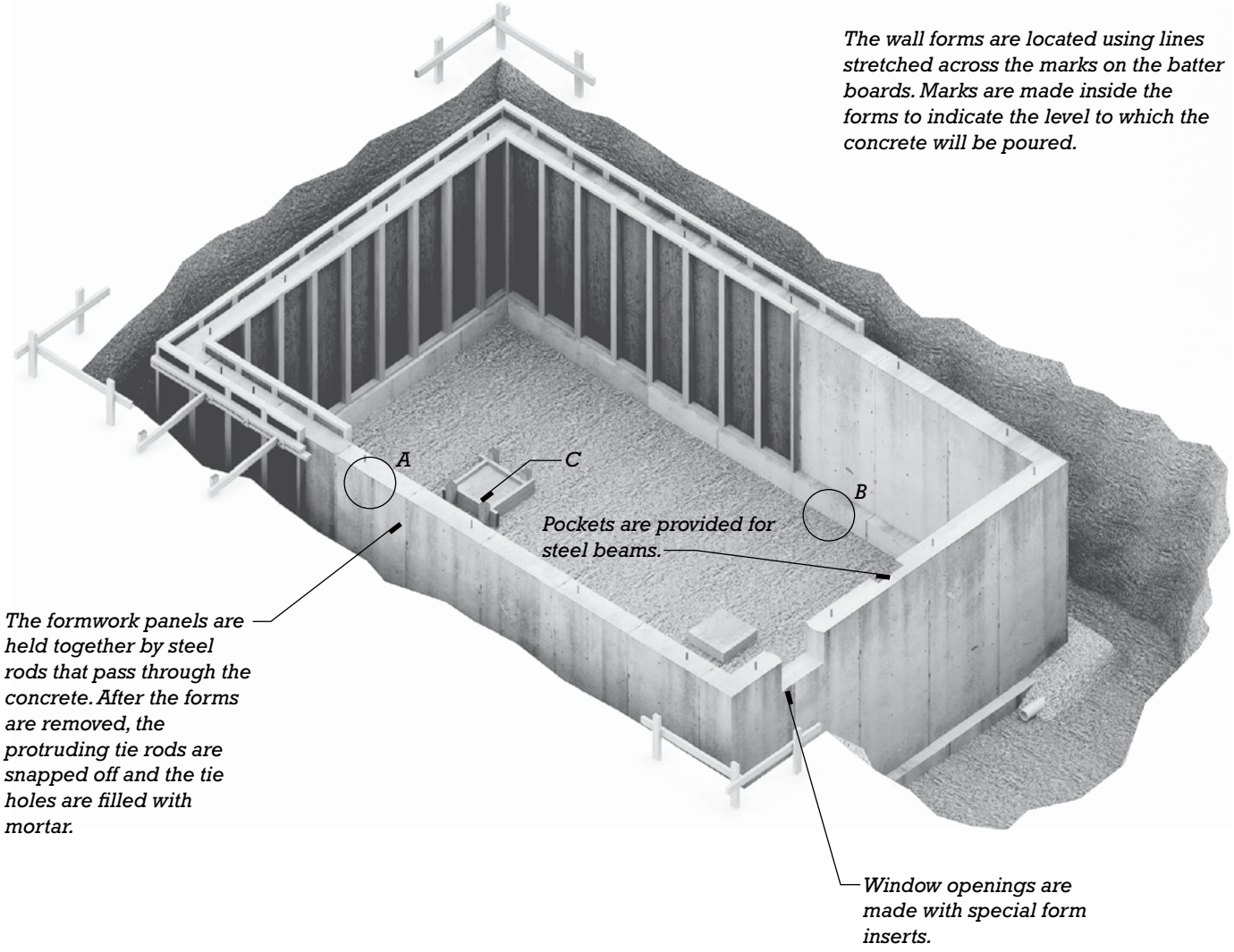


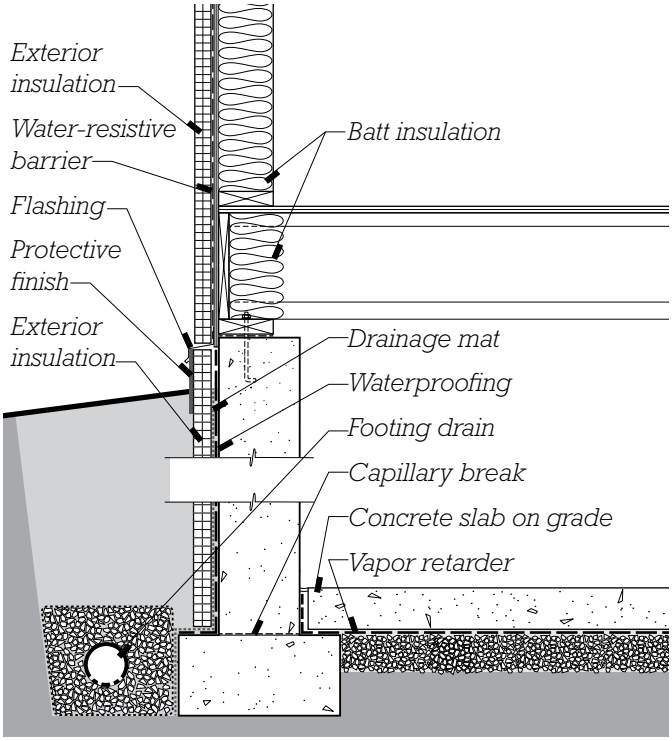
FIGURE 5.6

Typical details for a sitecast concrete foundation and basement for a platform frame building. Details *A*, *B*, and *C* are keyed to the circled portions of the drawing in Figure 5.7. You can download a PDF of this figure at *http://www.wiley.com/go/aflblce6ne*.

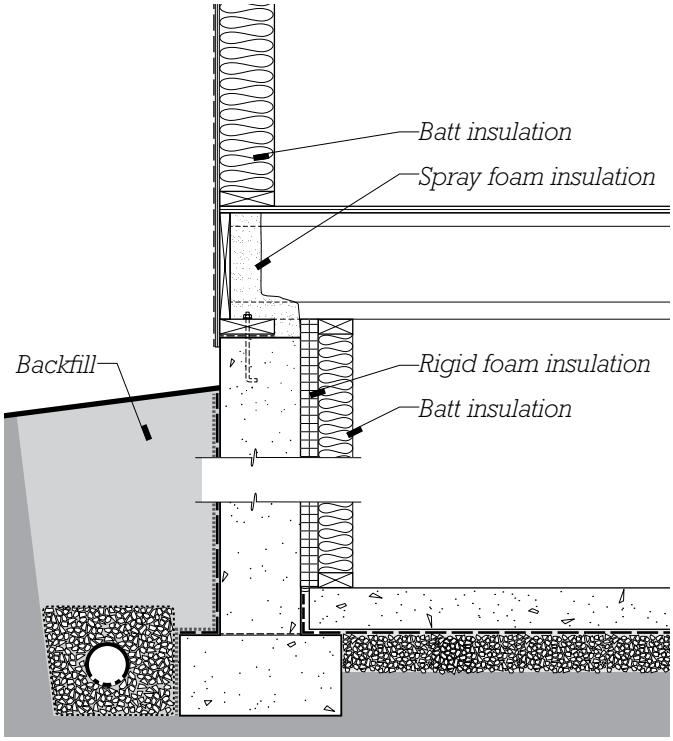


2

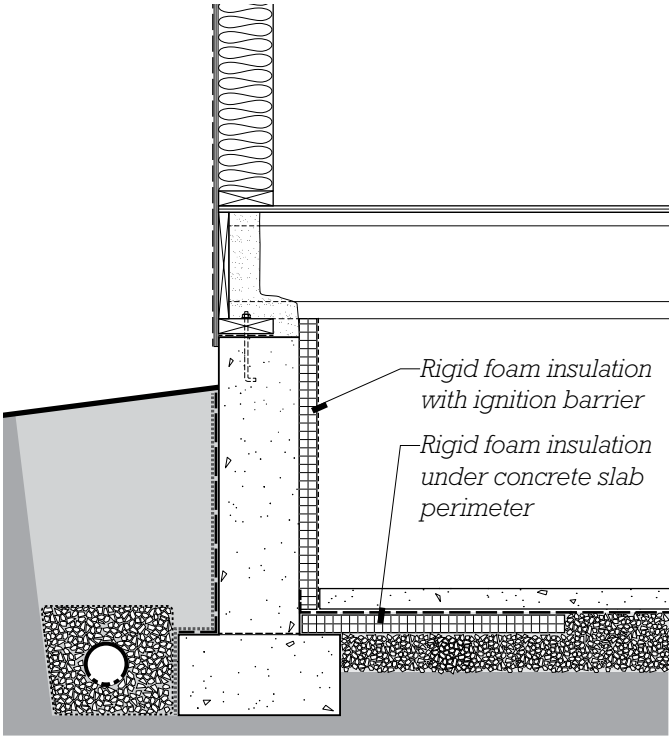
FIGURE 5.7
Step two in the construction of a typical platform frame building: excavation and foundation. The letters *A*, *B*, and *C* indicate portions of the foundation that are detailed in Figure 5.6.



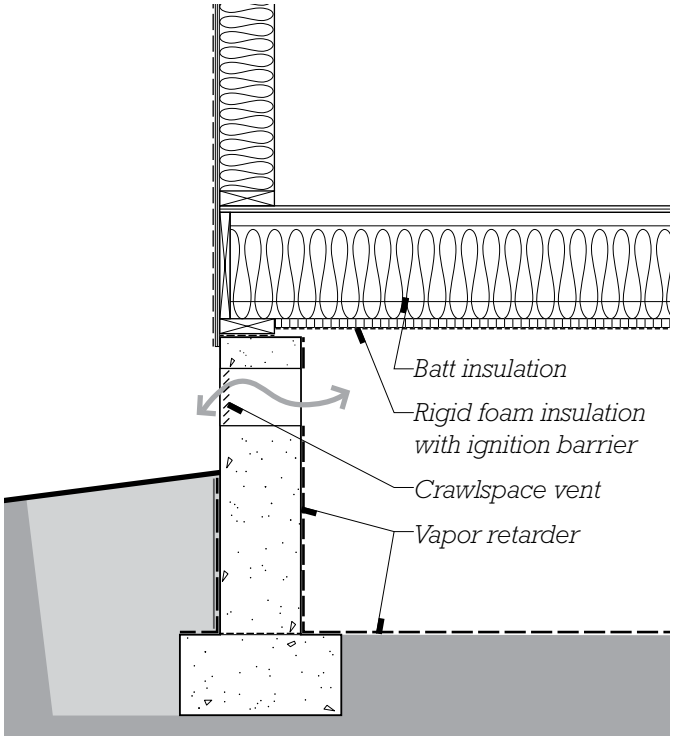
(A) BASEMENT WITH EXTERIOR INSULATION



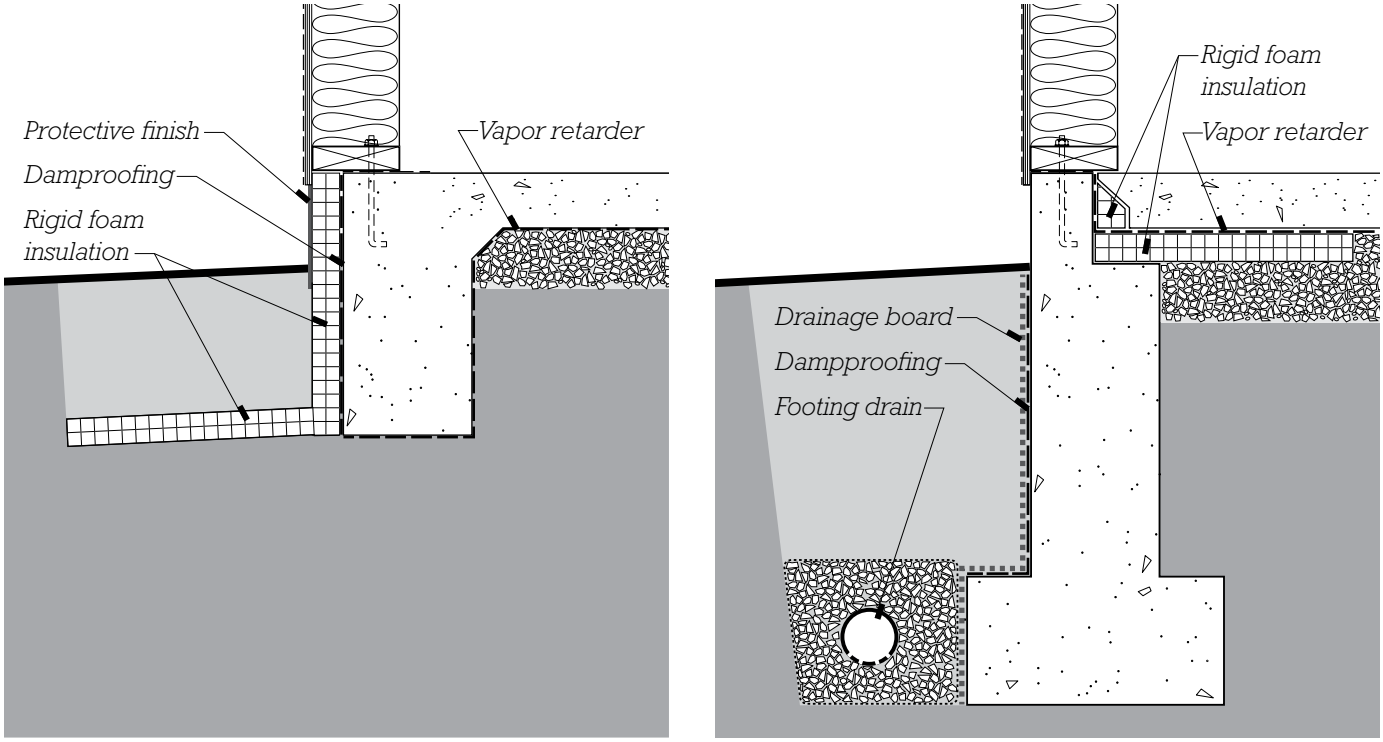
(B) BASEMENT WITH INTERIOR INSULATION



(C) CRAWLSPACE WITH INTERIOR INSULATION



(D) CRAWLSPACE WITH NATURAL VENTILATION



(E) SLAB ON GRADE WITH EXTERIOR INSULATION

(F) SLAB ON GRADE WITH SUBSLAB INSULATION

FIGURE 5.8

Foundation insulation strategies. The need for insulation and the amount varies depending on the climate zone and energy code requirements. (In these diagrams, exterior cladding, wall vapor retarders, if needed, and interior finishes are not shown.) *(A)* Foam plastic on the outside of the foundation wall can align with continuous insulation on the wall above. In full-height basements, insulation under the basement slab is not normally required. *(B)* When insulation is applied to the inside of the basement wall, air-impermeable rigid foam boards may be used to prevent warm interior air from reaching the cool concrete wall surfaces and causing condensation. The boards should be made airtight with taped or sealed joints. For additional insulation value, less expensive batt insulation can be added over the rigid boards. In the joist bay ends, spray foam is easier to install tightly in these irregular shaped spaces than rigid boards. When facing the building interior, plastic foam insulation must also be covered with a layer of gypsum wallboard or other fire-resistant material (not shown here) to delay the release of toxic gasses in the event of a building fire. *(C)* When crawlspaces are insulated, the strategies are much the same as for basements. However, because crawlspaces do not extend as deep into the ground, insulation under the perimeter areas of the slab (or over the ground surface if there is no slab) may also be required. Where plastic foam insulation is exposed in crawlspaces, it must be protected with an ignition barrier facing or finish material that reduces the risk of fire. *(D)* When a crawlspace is ventilated to the exterior, the floor above must be insulated. Rigid insulation underneath the floor joists, though not required by energy codes, reduces thermal bridging and protects the joists and insulation above from high humidity in the crawlspace. *(E)* When a slab on grade is connected to the foundation wall, insulation is applied to the exterior. The energy code requires a minimum depth of insulation that may extend downward or first downward and then outward from the foundation wall. *(F)* When the slab on grade and foundation wall are not connected, insulation may be applied under and around the edges of the slab.

FIGURE 5.9
Masons construct a foundation of concrete masonry. The first coat of parging, which is portland cement plaster applied to help dampproof the foundation, has already been applied to the outside of the wall, and the drainage layer of crushed stone has been backfilled in place. The projecting pilaster in the center of the wall will support a beam under the center of the main floor. After a second coat of parging, the outside of the foundation will be coated with an asphaltic dampproofing compound. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures*, 12th ed. Photos: Portland Cement Association, Skokie, IL.)*

FIGURE 5.10
Erecting formwork for a sitecast concrete foundation wall. The footing has already been cast and its formwork removed. It is visible in front of the worker at the left.
(Photo by Joseph Iano.)

FIGURE 5.11
Concrete foundation work in progress. The foundation wall has not yet been cast on top of the spread footing in the foreground. In the background, crawlspace walls are complete. Openings in the walls will have louvers installed to provide natural ventilation for an unconditioned crawlspace. The rectangular spread footing within the crawlspace is for a masonry chimney. *(Photo by Joseph Iano.)*

FIGURE 5.12
Concrete basement construction in progress. Anchor bolts are omitted from portions of the foundation wall where openings for doors or floor-level windows will be located in the wood-framed wall above. Liquid-applied waterproofing and a drainage mat (both dark in color) and polystyrene foam insulation have been applied to the outside of the wall.

Energy conservation codes require foundations to be insulated to reduce the exchange of heat with the surrounding soil (Figure 5.8). Some insulation materials (such as boards made of rigid plastic foam or mineral wool) are unaffected by moisture and sufficiently dense that they can be placed on the outside of the foundation wall prior to backfilling or under a slab on grade before the slab is poured. Many more insulation types can be applied to the inside of the foundation. Crawlspaces may either be ventilated to the exterior or treated as part of the heated or cooled building interior. When ventilated, the floor above the crawlspace is insulated. When the crawlspace is conditioned (heated or cooled), its walls and floor are insulated in manners similar to those for a basement.

FIGURE 5.13
Erecting a permanent wood foundation. One worker applies a bead of sealant to the edge of a panel of preservative-treated wood components as another prepares to push the next panel into position against the sealant. The panels rest on a horizontal preservative-treated plank, which, in turn, rests on a drainage layer of crushed stone. Wood foundations can be constructed in any weather and can be insulated in the same way as the superstructure of the building. *(Courtesy of APA–The Engineered Wood Association.)*

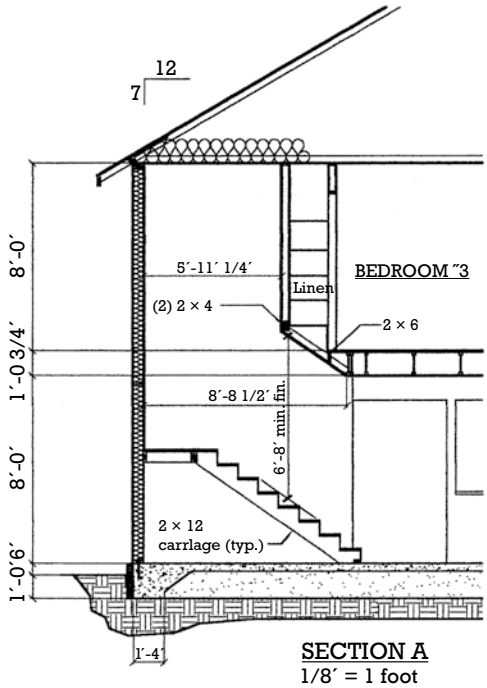
Other Foundation Materials

In extremely cold regions, where concrete and masonry construction methods are not practical, foundations may be made entirely of preservative-treated wood (Figure 5.13). Such *permanent wood foundations* can be constructed in any weather by the same crew of carpenters that will frame the remainder of the building. These foundations are readily insulated in the same manner as the frame of the house they support, and they easily accommodate the installation of electrical wiring, plumbing, and interior finish materials. Insulating concrete formwork (ICF) foundation systems using permanent insulating forms are easy to construct, eliminate the time and effort required to remove formwork, and provide integral insulation (see Figure 14.40). Precast concrete foundation systems relying on factory-fabricated reinforced concrete panels can be erected on site more rapidly than traditional sitecast concrete construction, although special attention is required to seal the joints between adjacent panels. They may be manufactured with insulation integral to the precast panel or designed to accept insulation applied on site after the panels are erected.

BUILDING THE FRAME

Planning the Frame

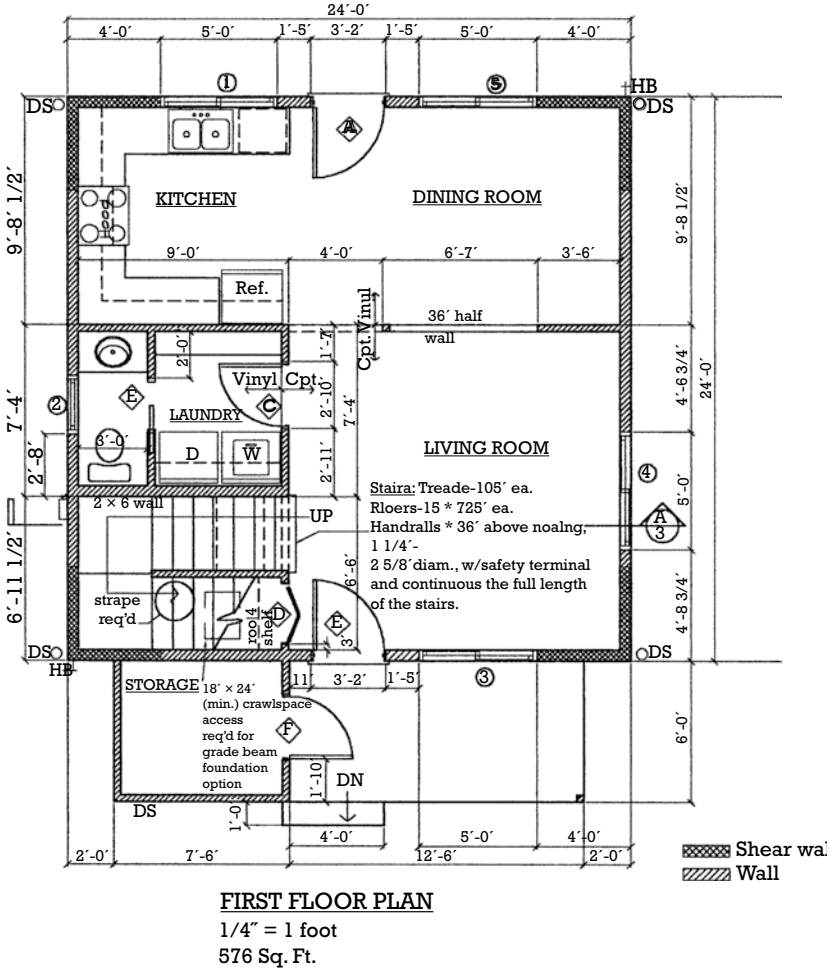
An experienced carpenter can frame a simple building from the most minimal drawings, but the framing for a larger or custom-designed structure may have to be planned as carefully as for a steel or concrete structure (Figure 5.14). The architect or engineer determines an efficient layout and the appropriate sizes for joists and rafters, and communicates this information to the carpenters by means of *framing plans* (Figures 5.15 and 5.52). For most purposes, member sizes can be determined using standardized structural tables that are part of residential building codes. Or, for more complex framing or special conditions, engineering may be required. Larger-scale *section details*, similar to those seen throughout this chapter, are prepared for major connections in the building system.



The *architectural floor plans* indicate the locations and dimensions of walls, partitions, and openings, and the *exterior elevations* show the outside faces of the building, with vertical dimensions or elevations indicated as required. For most buildings, *building sections* are also drawn that cut completely through the building, showing the dimensional relationships of the various floor levels and roof planes and the slopes of the roof surfaces. *Interior elevations* are often

FIGURE 5.14

A floor plan and building section are two important components of the construction drawings for a simple house with wood light framing. The ground floor is a concrete slab on grade. Notice that portions of the walls have been designated on the floor plan as shear walls; these are discussed later in this chapter.



FIRST FLOOR PLAN
1/4″ = 1 foot
576 Sq. Ft.

prepared for kitchens, bathrooms, and other rooms with elaborate interior features.

Erecting the Frame

The building of the platform frame structure is referred to as *rough carpentry*. The concept of platform frame construction, outlined in Figures 5.3 and 5.4, is illustrated in more detail in this chapter's sequential isometric diagrams, beginning with Figure 5.17, the first-floor platform. In succeeding illustrations, notice how each floor platform provides a ready work surface for the next step in the construction process. As a result, most of the work is accomplished without the use of ladders or scaffolding, and temporary bracing is needed only to support the walls until the next level of framing is installed and sheathed.

The details of a platform frame building—the sizes, spacing, and connections of its members, and even the size and number of nails for each connection (Figure 5.19)—are constructed according to industry standards and closely regulated by building codes. The most common of these details are shown in the figures accompanying the sequential isometrics, beginning with Figure 5.16.

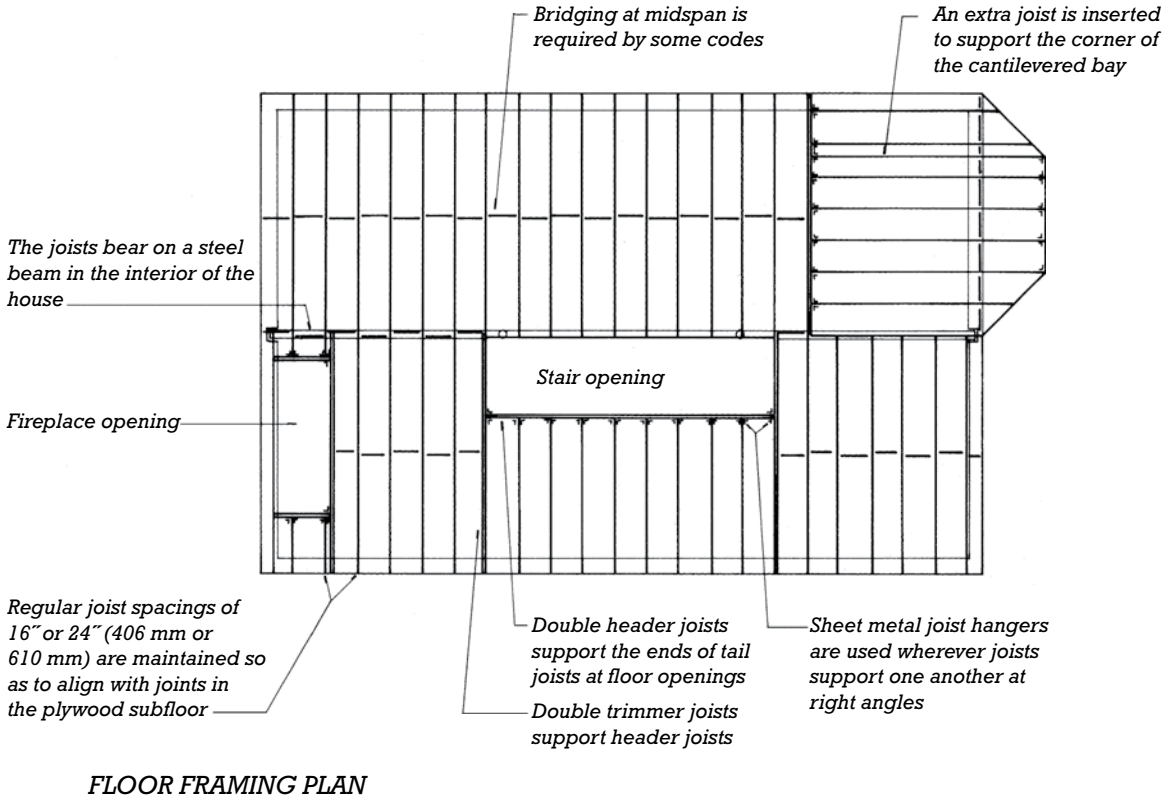
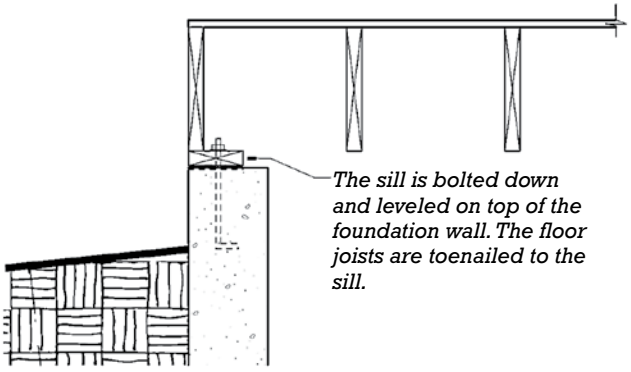
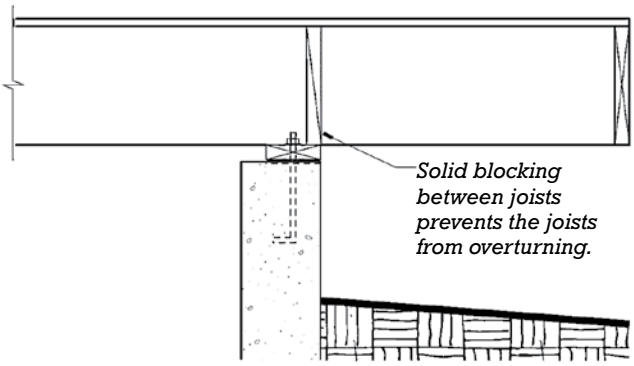


FIGURE 5.15
A framing plan for the ground-floor platform of the building shown in Figure 5.17.

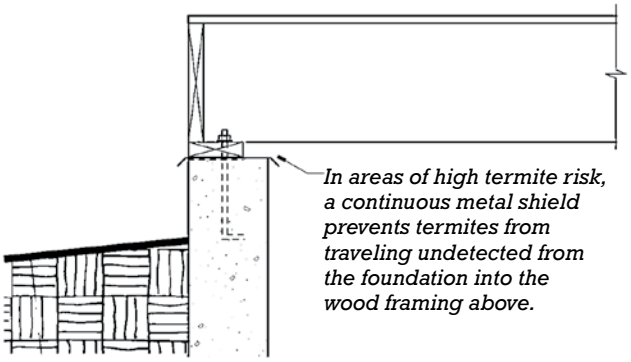
FIGURE 5.16
Ground-floor framing details for both solid lumber (*top*) and I-joist framing (*bottom*), keyed to the lettered circles in Figure 5.17. Continuous pieces of lumber are drawn with an *X* inside and intermittent blocking with a single diagonal. In both details *B*, framing members that cantilever beyond the foundation must either be preservative-treated or the deck construction must be carefully detailed to protect the framing from moisture and decay. The I-joist version shows cantilevered, preservative-treated solid lumber joists overlapped with the interior I-joist framing; several alternative framing strategies are also shown. (For clarity, webs of I-joists seen in elevation are shaded.)



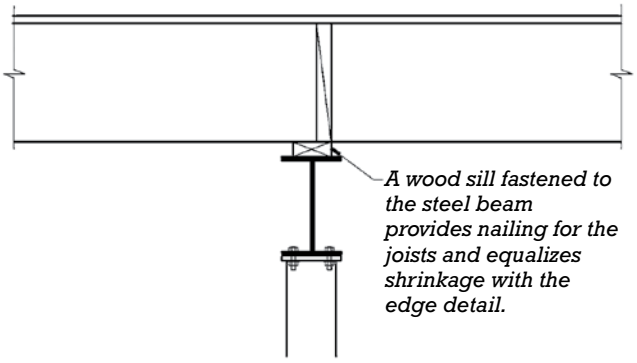
A. EDGE DETAIL AT END WALLS



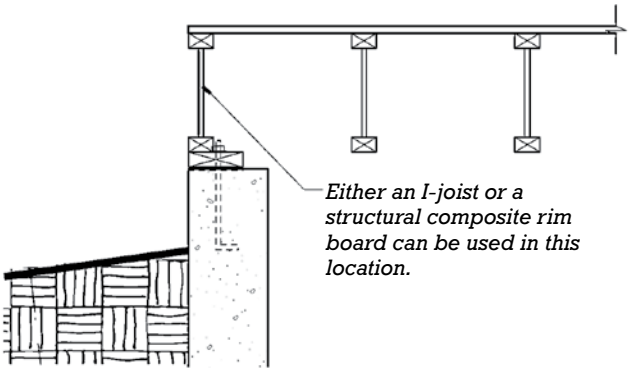
B. EDGE DETAIL AT CANTILEVERED JOISTS



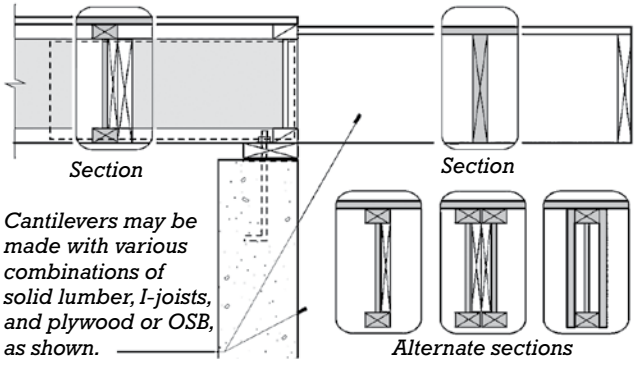
C. EDGE DETAIL AT SIDEWALLS



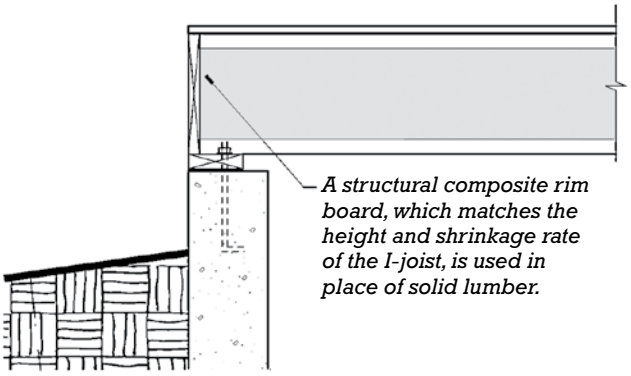
D. DETAIL OF INTERIOR JOIST BEARING



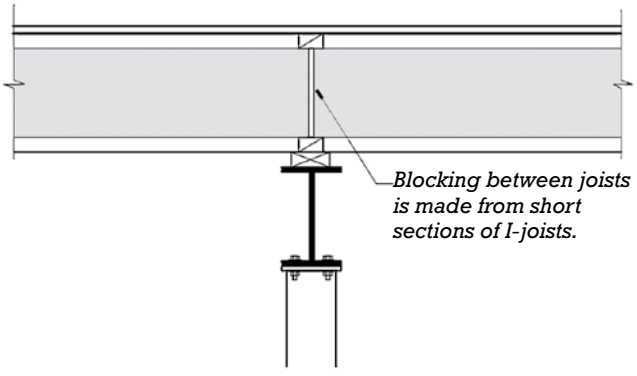
A. EDGE DETAIL AT SIDEWALLS



B. EDGE DETAIL AT CANTILEVERED JOISTS



C. EDGE DETAIL AT SIDEWALLS



D. DETAIL OF INTERIOR JOIST BEARING

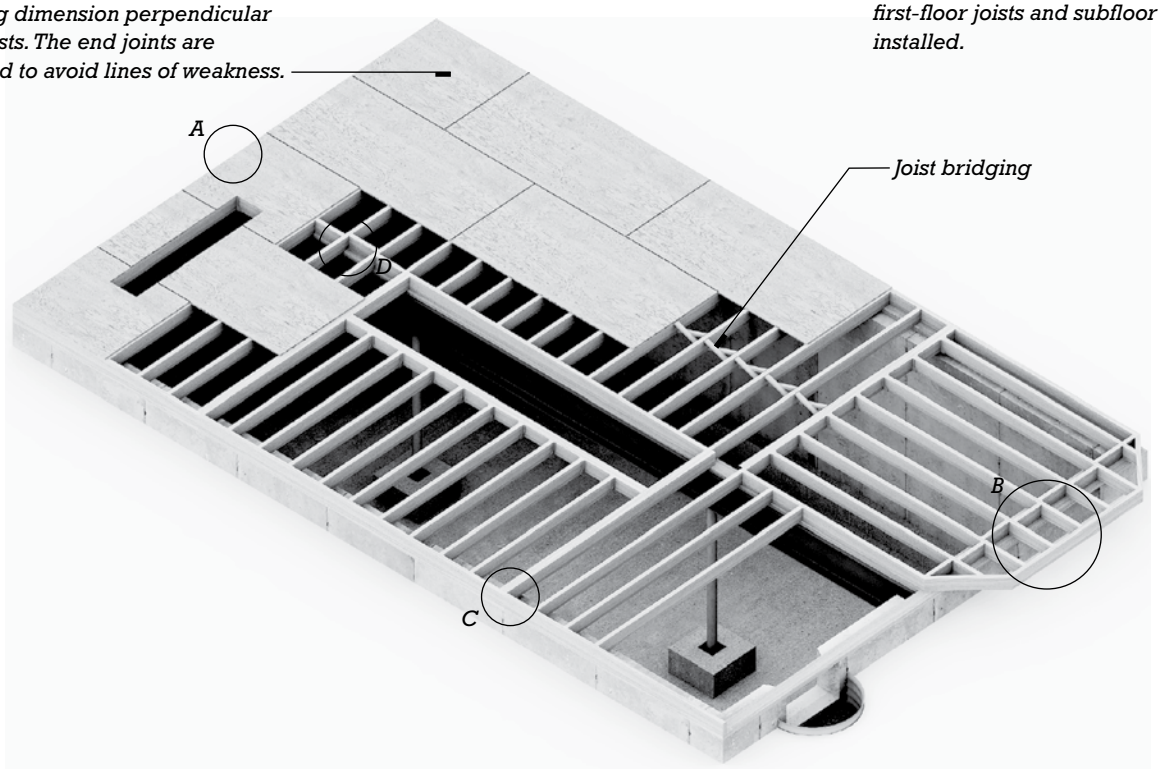
Attaching the Frame to the Foundation

The *foundation sill plate* (sometimes also called a *mudsill*), made of preservative-treated wood for resistance to insects and moisture, is attached to the top of the foundation to serve as a base for the wood framing to follow (Figure 5.16, *A*, *B*, and *C*). A single nominal 2-inch (38-mm) sill, as shown in the details here, may be all that is required. Or, where seismic or wind design forces are high, the sill may be doubled or made from thicker stock for added stiffness and to create a stronger connection between the foundation and the wood frame above. At a minimum, the sill is fastened in place with ½-inch (13-mm) anchor bolts, embedded in the top of the foundation wall and spaced not more than 6 feet (1829 mm) apart. Alternatively, similarly spaced proprietary sheet metal anchor straps may be used instead of bolts.

Because the top of a foundation wall is likely to be somewhat uneven, the sill is shimmed up at low spots with wood shingle wedges or plastic shims to provide a more level base for subsequent framing. (The term "mudsill" is a carryover from times when the sill was set in a bed of cement mortar, or "mud," to accomplish the same purpose.) A *sill seal*, or *sill gasket*, made of any of a number of compressible or resilient materials, is inserted between

Plywood sheets are considerably stiffer along their length than across their width, so they must be laid with their long dimension perpendicular to the joists. The end joints are staggered to avoid lines of weakness.

When the foundation is complete, basement beams are placed, sills are bolted to the foundation, and the first-floor joists and subfloor are installed.



3

FIGURE 5.17

Step three in erecting a typical platform frame building: the ground-floor platform. Compare this drawing with the framing plan in Figure 5.15. Notice how the direction of the joists changes to construct the cantilevered bay on the end of the building. A cantilevered bay on a long side of the building could be framed by merely extending the existing floor joists over the foundation. The bridging shown between joists is discussed later in this chapter. The letters *A*, *B*, and *C* represent portions of the framing detailed in Figure 5.16. Methods of supporting floor joists over steel or wood beams are shown in Figure 5.18.

Interactive Exercise

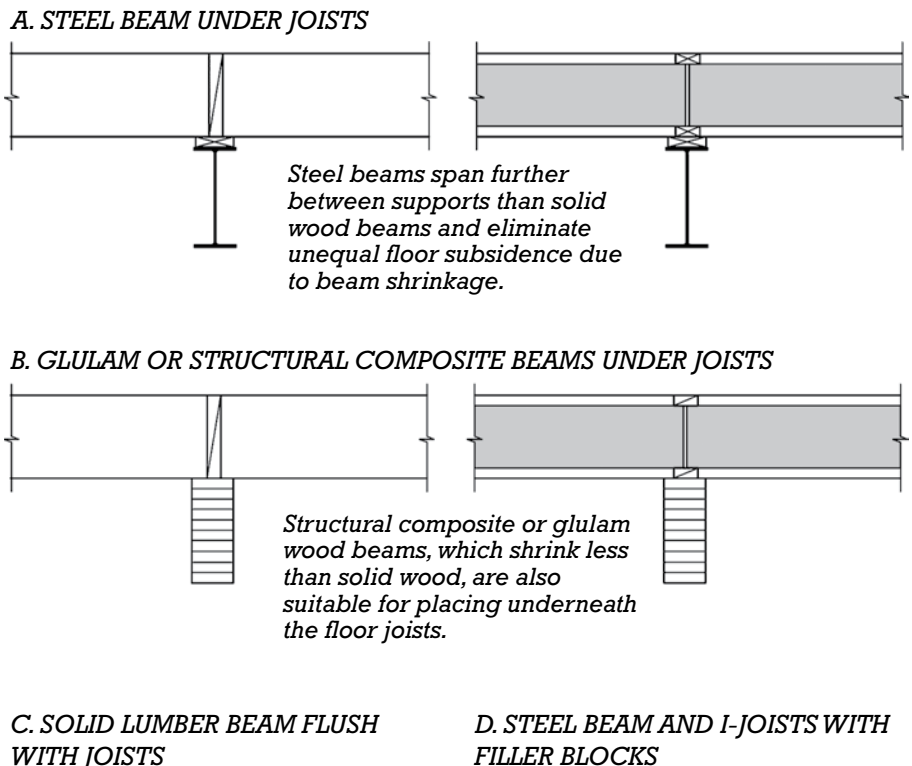


FIGURE 5.18

Methods of beam support for lumber joists (*left column*) and I-joists (*right column*) between foundation walls. Where joists pass over the top of the beam (*A*, *B*), beams made of steel, glue-laminated wood, or structural composite lumber should be used. Solid lumber beams should be avoided in this application, as their greater drying shrinkage can cause noticeable subsidence in the floor. Solid lumber beams should be framed flush with the joists (*C*) so that their shrinkage occurs in parallel with the joists. Ways to frame joists flush with steel beams are shown in *D*, *E*, and *F*. In *D*, the bottoms of the joists are above the bottom flange of the beam, and filler blocks are bolted to the web of the beam to restrain the joists from sidesway in the case of a seismic event. Filler blocks also allow the use of face-mounted joist hangers, rather than top-mounted as shown here. In *F*, the joists are deep enough to be restrained by the bottom flange of the steel beam and no filler blocks are required. In *E*, a small space must be left over the top of the beam to allow for drying shrinkage in the joists.

Connection	Nailing	Nails
Girders and beams built up from nominal 2" (38-mm) lumber	Face nail, staggered top and bottom edges	20d common @ 32" (800 mm) o.c. or 10d common @ 24" (610 mm) o.c.
Floor joist ends to plate or beam below	Toe nail	4-8d box, 3-8d common, or 3-10d box
Joists to headers, headers to trimmers	Use joist hangers	
Bottom plate to joist or blocking below, unbraced walls	Face nail	16d common @ 12" (305 mm) o.c.
Bottom plate to joist or blocking below, braced walls	Face nail	3-16d box or 2-16d common, @ 16" (406 mm) o.c.
Stud to bottom plate or top plate	Toe nail	4-8d box, 3-16d box, 4-8d common, or 4-10d box
Stud to bottom plate or top plate	End nail	3-16d box, 2-16d common, or 3-10d box
Double studs in unbraced walls	Face nail	16d common nail @ 24" (610 mm) o.c., or 10d box nail @ 16" (406 mm) o.c.
Double studs in braced walls, built-up corner studs	Face nail	16d box @ 12" (305 mm) o.c., or 16d common @ 16" (406 mm) o.c.
Double top plate	Face nail	16d common @ 16" (406 mm) o.c., or 10d box @ 12" (305 mm) o.c.
Ceiling joist ends to sill or top plate	Toe nail	4-8d box, 3-8d common, or 3-10d box
Rim joist to top plate	Toe nail	8d box @ 4" (101 mm) o.c., or 8d common or 10d box @ 6" (152 mm) o.c.
Rafter or truss to top plate	Toe nail	3-16d common, 3-10d common, or 4-10d box
Rafter to ridge board, valley, or hip rafter	Toe nail	4-16d box, 3-10d common, or 4-10d box
Rafter to ridge board, valley, or hip rafter	End nail	3-16d box, 2-16d common, or 3-10d box
Rafter to ceiling joist	3 to 39 end nails, depending on roof slope, rafter spacing and span, and snow loads	16-d common
Rafter to collar tie	Face nail	4-10d box or 3-10d common
Wood structural panel sheathing up to ½" (13 mm) thick	Face nail 6" (150 mm) o.c. at edges and 12" (300 mm) o.c. at intermediate supports	6d common for floors and walls, 8d common for roof
Structural sheathing up to 1" (25 mm), subfloors, interior walls, exterior walls, and roofs	Same as above	8d common

FIGURE 5.19
A partial list of standard nailing for platform frame construction. These requirements are incorporated into building codes, and experienced framing carpenters know them by heart. For fastening of framing members, either common or box nails are permitted. Structural sheathing must be nailed with common nails only. Where sinkers are used, larger penny sizes than indicated may be needed to meet the minimum length and shaft diameter requirements. Despite the apparent complexity of this list, it is possible to simplify the number of nails types required for rough framing work. For example, most of the above can be accomplished with just a 16d common nail and an 8d common nail. For example, where this table indicates 10d nails face nailed into two nominal 2-inch members (3 inches, or 76 mm, in combined thickness), a 16d nail (3½ inch, or 89 mm, long) can be used, driven at an angle so that its pointed end does not protrude from the opposite side.

the sill and the foundation to reduce air infiltration through this gap and to restrict moisture wicking up from the foundation into the wood framing (Figure 5.20). Where the risk of termite infestation is high, metal *termite shields* may be inserted between the foundation wall and the sill. These prevent termites from traveling undetected from cracks in the concrete up into the wood framing. As discussed later in this chapter, where wind and earthquake forces are high, additional measures may be taken to further strengthen the frame-to-foundation connection.

Floor Framing

Solid lumber floor joists typically range in size from 2 × 6 (38 × 140 mm) for lightly loaded floors and short joist spans, to 2 × 12 (38 × 286 mm) for heavier loads and longer spans. They are most commonly spaced at 16 or 24 inches (406 or 610 mm) o.c. As can be seen in Figure 5.17, this ensures support for the ends of the subflooring at 4-foot (1220-mm) intervals, as occurs when 8-foot (2440-mm)-long panels are laid with their end joints staggered in adjacent rows. For heavy loads or long spans, but where a deeper joist is not practical, a closer joist spacing, such as 12 inches (305 mm) o.c., may also be used.

FIGURE 5.20
Carpenters apply a preservative-treated wood sill to a sitecast concrete foundation. Compressible glass fiber sill seal has been placed on the top of the concrete wall, and the sill has been drilled with snugly fitting holes at anchor bolt locations. Before each section of sill is bolted tightly, it is leveled as necessary with wood shingle or plastic shims between the concrete and the wood. As the anchor bolts are tightened, the sill seal squeezes down to a negligible thickness. A section of bolted-down sill is visible at the upper right. The basement windows were clamped into reusable steel form inserts and placed in the formwork before the concrete was cast. After the concrete was cast and the formwork was stripped, the steel inserts were removed, leaving a neatly formed concrete frame around each window. A pocket in the top of the wall for a steel beam can be seen at the upper left. *(Photo by Edward Allen.)*

FIGURE 5.21
Installing solid lumber floor joists. Also visible in the face of the rim joist are the toe nails in the sill and the end nails in the floor joists. *(Photo by Edward Allen.)*

FIGURE 5.22
Wood crossbridging for I-joists. Bridging installation begins from above, before the subflooring is laid. Fastening of the bottom ends must be completed from below, so, as seen in this photograph, it is frequently deferred until later. Note the printing "TUBING ABOVE AVOID DAMAGE" on the underside of the subflooring panels, indicating hydronic heating tubes installed in upper side of the panels. *(Photo by Joseph Iano.)*

Joists, which rest on their narrow edges, must be restrained from overturning. At a minimum, this is accomplished by end nailing through the rim joists into the joist ends (Figure 5.21). In areas subject to high seismic forces, additional overturning resistance is provided by lines of solid blocking inserted between joists over floor beams, bearing walls, and other intermediate lines of joist support. Additionally, where solid joists exceed 12 inches (286 mm) in depth, *bridging* (solid blocking, crossbracing, or strapping) must be inserted at intervals not exceeding 8 feet (2.4 m) (Figures 5.22 and 5.23). Blocking or bridging are also sometimes installed into floors framed with members less than 12 inches in nominal depth, to improve stiffness and reduce vibration in the floor system.

Where floor openings occur, such as for stairs or chimneys, headers and trimmers are used to frame the opening and carry the floor loads around the opening to supporting walls or beams. For larger openings, these members are doubled to account for the greater loads that they must carry. Where the ends of joists meet a supporting header, nailing alone cannot be relied upon to transfer loads between the members, so sheet metal joist hangers are used. Each hanger provides a secure pocket for the end of the joist and punched holes into which properly sized nails are driven to make the connection. Extra joists may also be inserted into the floor framing anywhere concentrated loads from above are expected, such as underneath bathtubs or load-bearing walls.

Today, manufactured I-joists are as likely to be used for floor framing as solid lumber (Figure 5.24).

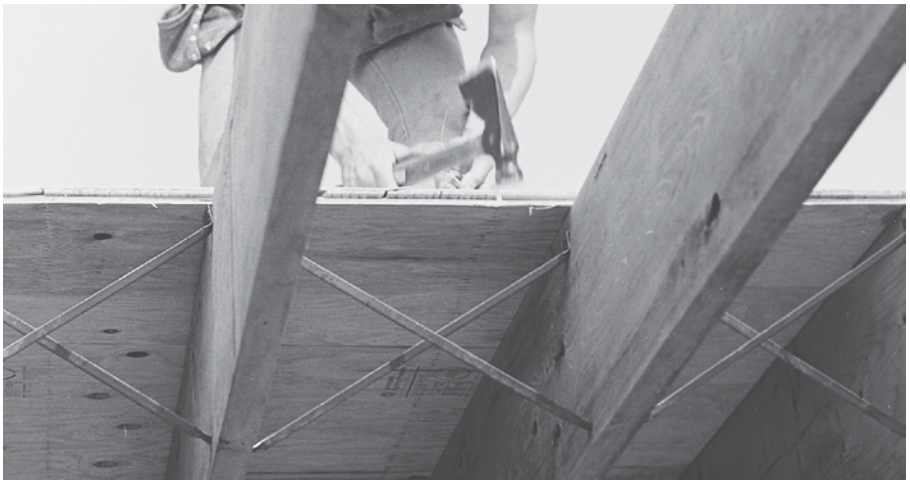


FIGURE 5.23
Metal crossbridging for solid wood joists. The steel strip is manufactured in a folded V-shape for increased stiffness. One or both ends of the brace may be toothed, to allow installation directly into the joist without the need for nails. *(Courtesy of APA–The Engineered Wood Association.)*

FIGURE 5.24
A floor platform being framed with manufactured I-joists. The joists in this photograph are made with laminated veneer lumber (LVL) flanges and plywood webs. Note the ease with which one carpenter can lift this relatively long but lightweight member. *(Courtesy of Trus Joist MacMillan.)*

Compared to solid wood joists, these components are lighter in weight, can span greater distances, provide greater straightness and uniformity, and reduce drying shrinkage of the floor platform. I-joists can also more easily accommodate piping, ductwork, and wiring within the floor platform, as openings (sized and located so as not to impair the structural capacity of the joist) can be made in the relatively thin web of the I-joist more easily than in solid lumber. Some I-joists are manufactured with preformed web knockouts, ensuring that openings are both easy to make and properly located and sized.

I-joists range from 9½ to 24 inches (241 to 610 mm) in depth, with flanges from 1¾ to 3½ inches (44 to 90 mm) wide. They are capable of spanning up to approximately 30 feet (9 m). For normal loads and spans, joists are most commonly spaced at 24 inches (610 mm) o.c. However, closer spacings may be used for longer spans, greater floor loads, or increased floor stiffness.

The relatively thin webs of the I-joist may require special consideration in joist connection details. For example, where a joist hanger is not tall enough to restrain both the top and bottom flanges of the joist, *web blocking* is inserted on either side of the web to restrain the joist from tipping sideways (Figure 5.25).

Various types of web blocking or stiffening are also used where the loads applied to I-joists at their ends or at points of intermediate support are high enough to buckle or crush the joist web, as shown in Figure 5.47. Bridging and blocking, installed to resist joist overturning or stiffen longer spans, are used with I-joists in the same manner as described for solid lumber joists. Manufactured floor trusses (Figure 5.26), like I-joists, can span farther than solid wood joists, reduce shrinkage in the floor platform, and provide natural openings to accommodate building services.

In comparison to solid wood joists that provide only 1½ inches (38 mm) of supporting surface for the subfloor above, the top surfaces of I-joists and floor trusses may be as wide as 3½ inches (64 to 89 mm). This allows an opportunity for additional possible economy in the use of these member types. Where solid joists are spaced at 16 inches (406 mm) o.c., it may be possible to space trusses or I-joists at 19.2 inches (488 mm) without having to increase the thickness or strength of the subflooring. This is possible because the wider top surface effectively reduces the span of the subfloor panels between the joists. This small change in joist spacing, which requires one less joist over every 8 feet (2440 mm), results in a 17 percent reduction in joist framing materials and installation labor.

Subflooring is installed after floor framing is complete. The subfloor panels are laid with their longer dimension perpendicular to the framing on which they are supported, as the panels are considerably stiffer in this orientation (Figure 5.27). With plywood subflooring, which typically has different veneer grades on either side, the panel is laid with the better grade facing up. A ⅛-inch (3-mm) gap is maintained around all panel edges to prevent buckling caused by the expansion of rain-wetted panels. To reduce squeaking in the finished floor and increase floor stiffness, adhesive may be applied to the tops of joists before the panels are laid, and deformed shank nails or self-drilling screws with greater withdrawal resistance than plain common nails may be used for fastening (Figure 5.28).

FIGURE 5.25
I-joist web blocking at a sheet metal joist hanger. The blocking is applied to both sides of the web to restrain the joist from rotating within the hanger. Alternatively, if a taller hanger capable of restraining both the top and bottom flanges of the joist is used, blocking is not required for this purpose. Web blocking may also be used to stiffen the relatively slender web to prevent it from buckling under heavy loads, such as when a bearing wall rests on the platform directly above. As can be seen in the photograph, web blocking should be cut slightly shorter than the joist web itself, so that if the web compresses slightly under the load, the blocking does not pry the top flange apart from the web. *(Photo by Joseph Iano.)*

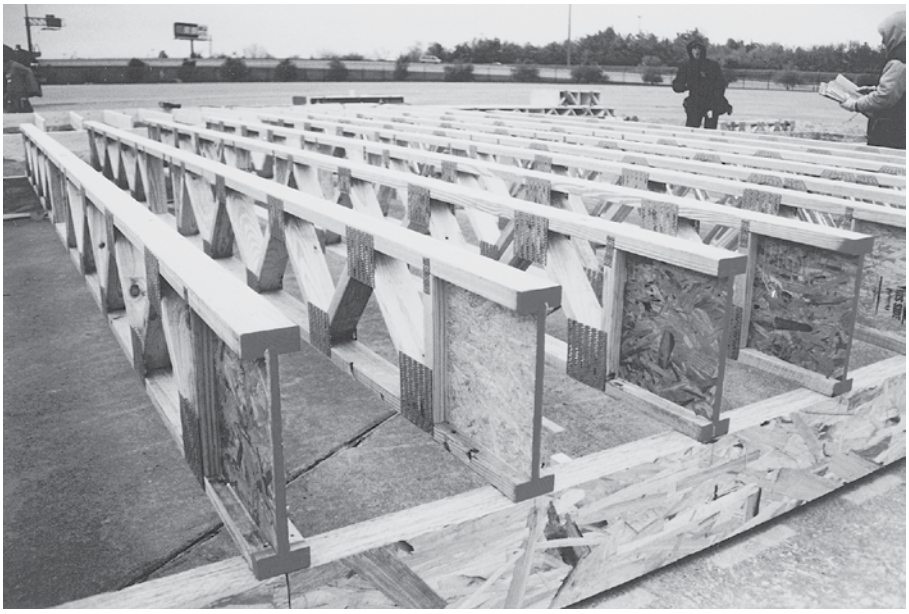


FIGURE 5.26
These floor trusses (shown here being set up for a demonstration house in a parking lot) are made of sawn lumber members joined by toothed-plate connectors. The OSB web at each end provides a section of truss that can be sawn by workers to easily adjust the length of the truss as necessary. Trusses are deeper than solid wood joists or I-joists but can span farther. Even though they are deeper than other joist products, they may result in a thinner floor/ceiling assembly, as pipes and even relatively large sections of ductwork can run through the passages within the truss rather than below it. *(Courtesy of the Wood Truss Council of America.)*

FIGURE 5.27
Applying OSB subflooring. Note that the longer dimension of the panel runs perpendicular to the joist framing. *(Courtesy of APA–The Engineered Wood Association.)*

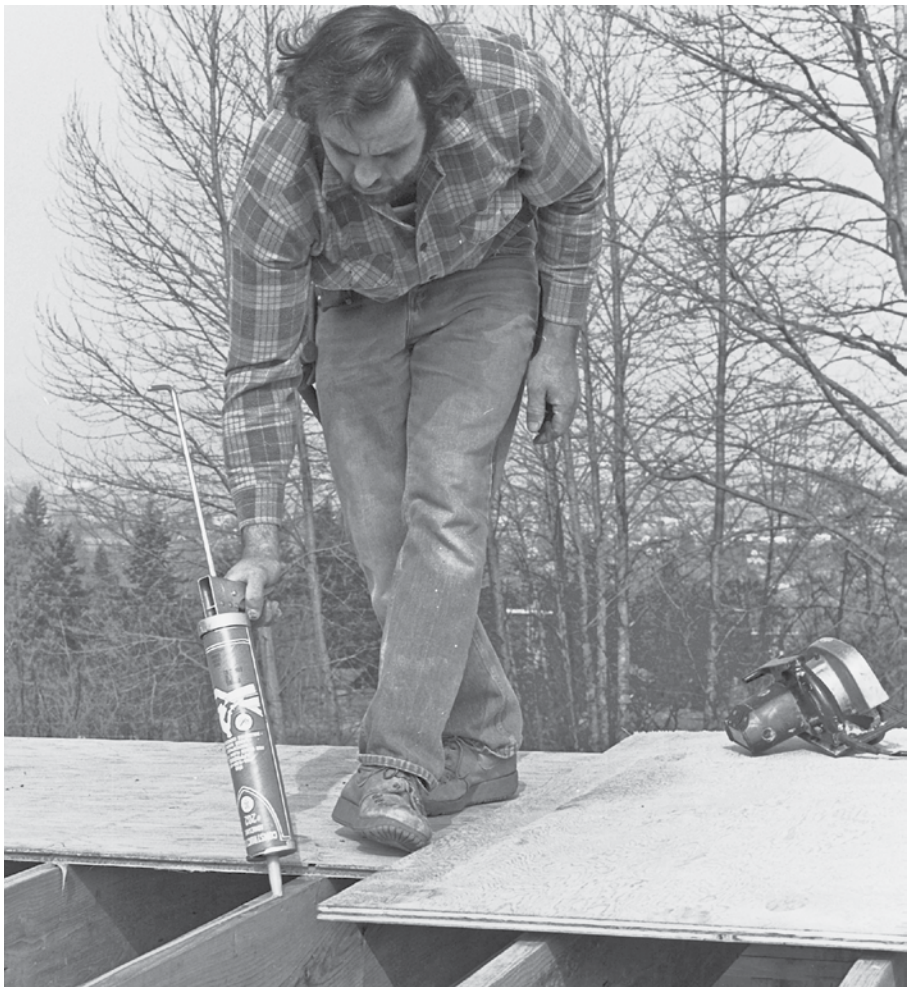


FIGURE 5.28
For a stiffer, quieter floor, subflooring may be glued to the joists. The adhesive is a thick mastic that is squeezed from a sealant gun on the tops of the joists just before the subflooring is laid in place. *(Courtesy of APA–The Engineered Wood Association.)*

Wall Framing

Walls are usually framed with 2 × 4 (38 × 89 mm) or 2 × 6 (38 × 140 mm) members—the deeper 2 × 6 being used to support greater loads or provide more space for insulation in the wall. Solid lumber studs are most common. However, structural composite or finger-jointed lumber may also be used. Like floor joists, wall studs are spaced at 16 or 24 inches (406 or 610 mm) to coordinate with the 4-foot (1.2-m) module of exterior sheathing and interior wallboard panels. Studs are nailed in place between top and bottom plates made from the same size lumber as the studs. With loadbearing walls, the top plate is doubled for greater strength and stiffness, and to help with the transfer of the loads from above into the studs below. Walls are constructed in sections lying down, using the previously built floor platform as a work surface. When ready, they are tilted up, plumbed (set vertical), and nailed into position, with temporary bracing applied to hold them in position until adjoining framing is completed (Figures 5.29 through 5.36).

Openings for windows and doors are formed with headers, trimmers,

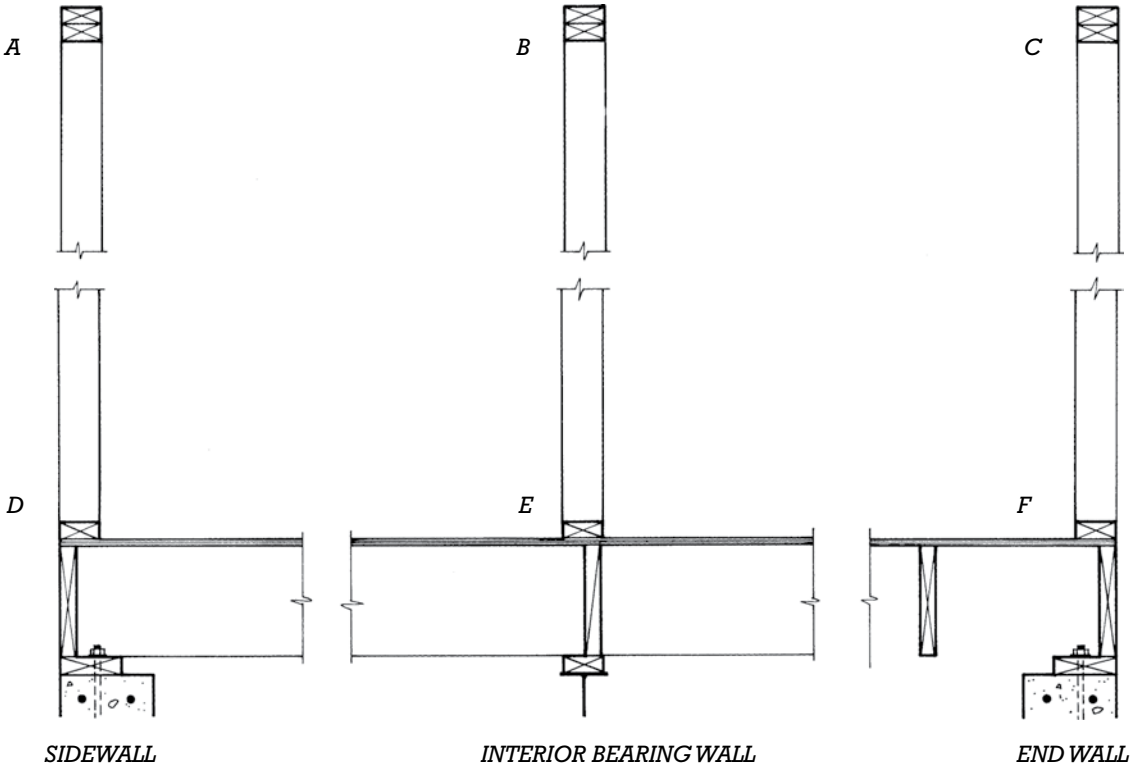
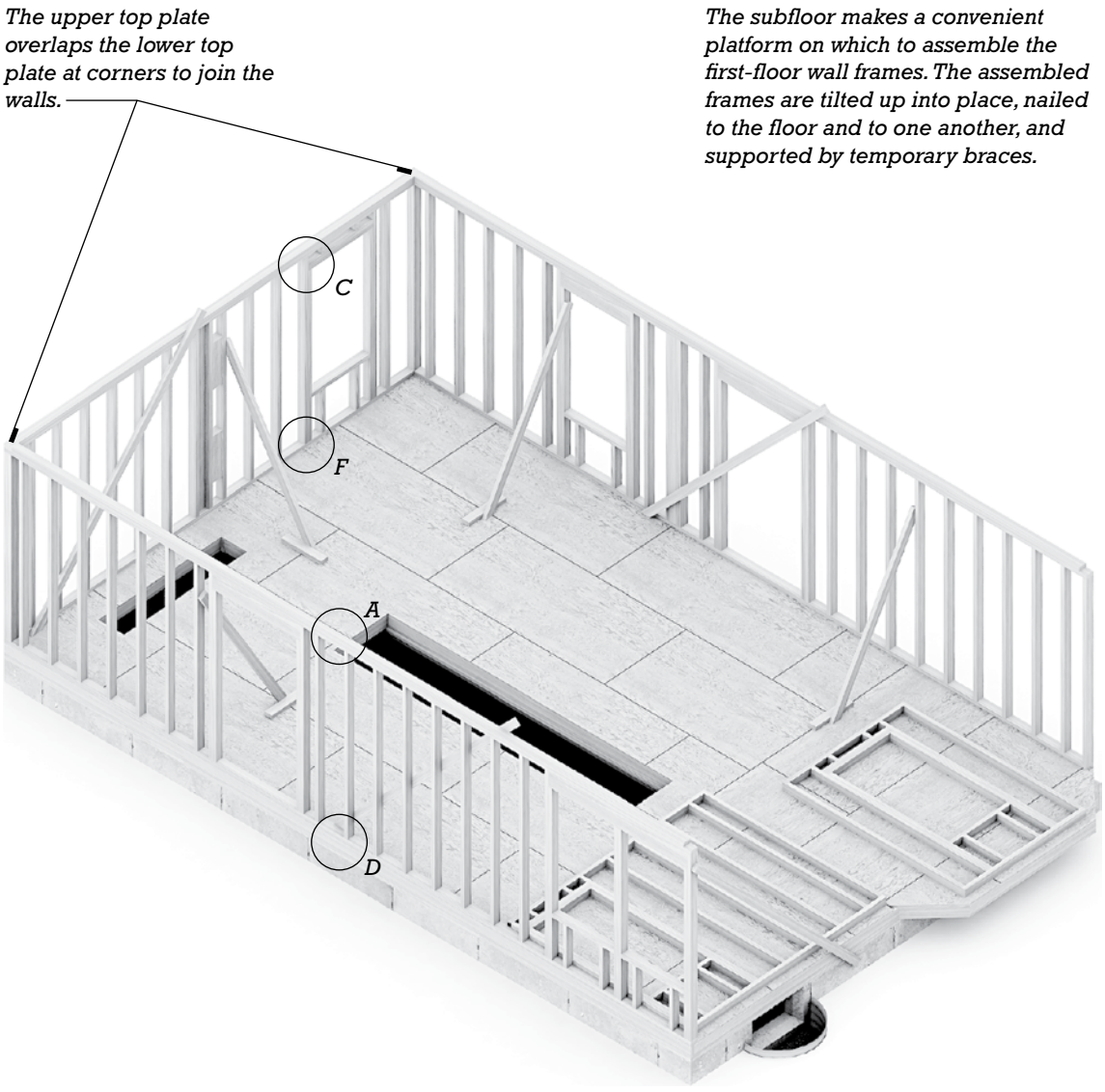


FIGURE 5.29
Typical ground-floor wall framing details, keyed by letter to Figure 5.30.

Interactive Exercise

and sills. Headers, spanning across the top of an opening, take the loads from above the opening and carry them to either side. They are made from two members on edge, with material sandwiched between so that their total width is equal to that of the wall. The depth of the header varies according to the work it must perform: shallow for light loads and short spans, and deeper for larger loads and longer spans. Where they are needed, structural composites with greater strength, such as LVL or PSL, may be used. Prefabricated headers that include integrated thermal insulation to reduce heat loss through these difficult-to-insulate areas may also be used. At either end, headers rest on shortened studs called "trimmers," or *jack studs*, which themselves are nailed to full-height *king studs*. At the bottom of a window opening, the *rough sill* is supported on *cripple studs* (Figure 5.32).

Where walls intersect, nailing surfaces must be provided for supporting the edges of the exterior sheathing and interior wallboard. This requires at least three studs at each intersection, unless special metal clips are used to reduce the number to two (Figure 5.32).



4

FIGURE 5.30
Step four in erecting a platform frame building: The ground-floor walls are framed. The letters *A*, *C*, *D*, and *F* indicate portions of the framing that are detailed in Figure 5.29.

Walls exceeding 10 feet (3 m) in height must have solid blocking inserted at midheight to limit the volume of the wall cavities and reduce the ease with which fire can spread within the wall. Where long, consistently straight pieces of solid lumber are not readily available for the construction of unusually tall walls, structural composite or finger-jointed stock may be used.

Wall sheathing, most frequently plywood or OSB, provides a nailing surface for exterior cladding materials and stiffens the wall against the lateral forces of wind and earthquake. Other sheathing panel types, made from wood or paper fiber, plastic foam, or glass or mineral fiber, are intended principally as thermal insulation and to provide a base for building paper, housewrap, or other weather-resistant coverings. Where walls are sheathed with such nonstructural panels, *let-in diagonal* bracing can be used to provide lateral force resistance. Let-in bracing may be made of 1 × 4 (19 × 89 mm) wood boards or of light steel members that are recessed into the outer face of the studs of the wall before it is sheathed (Figures 5.32 and 5.37). However, let-in bracing is

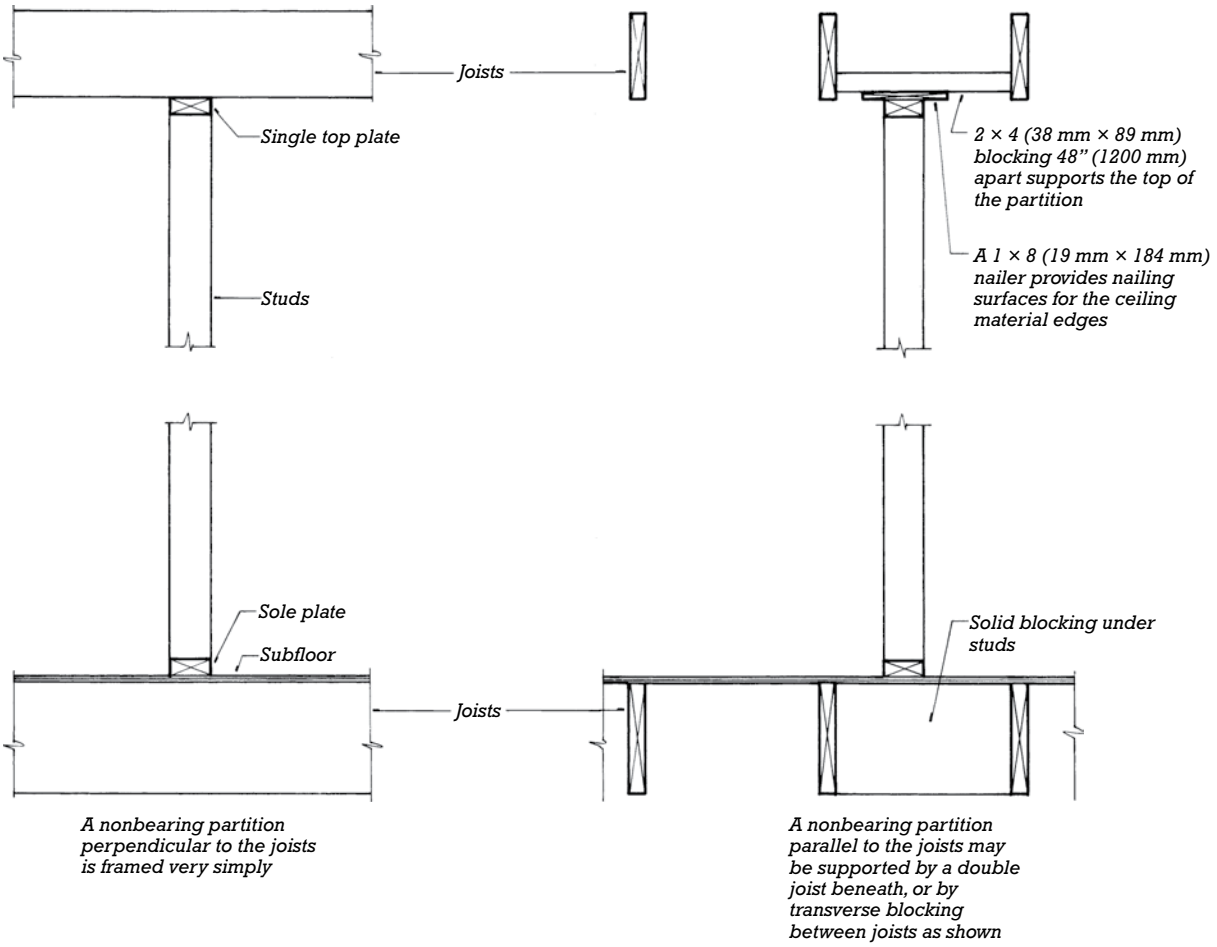
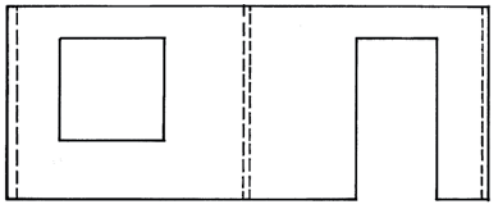
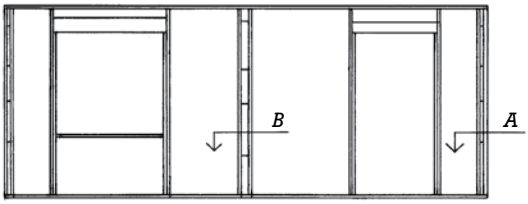


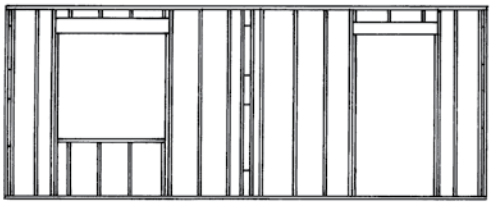
FIGURE 5.31
Framing details for nonloadbearing interior partitions.



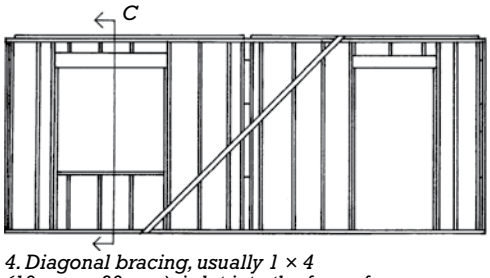
1. This is the layout of a typical exterior wall. It meets two other exterior walls at the corners, and a partition in the middle. It has two rough openings, one for a window and one for a door.



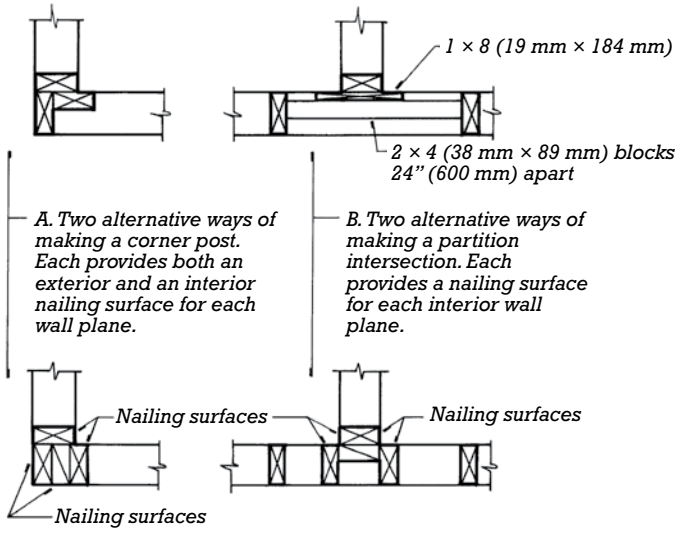
2. The framer begins by marking all the stud and opening locations on the sole plate and top plate. The "special" studs are cut and assembled first: two corner posts, a partition intersection, and full-length studs and supporting studs for the headers over the openings.

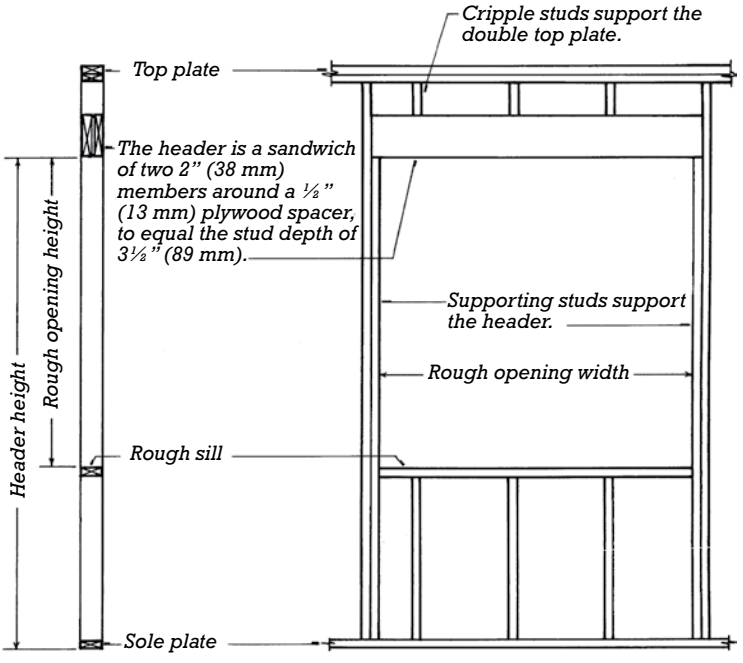


3. The wall is next filled with studs on a regular 16" (400 mm) or 24" (600 mm) spacing, to provide support for edges of sheathing panels.



4. Diagonal bracing, usually 1 × 4 (19 mm × 89 mm), is let into the face of the frame if the building will not have rigid sheathing. The second top plate may be added before the wall is tilted up, or after.





C. SECTION THROUGH A WINDOW OPENING

D. ELEVATION OF A WINDOW OPENING

FIGURE 5.32

Steps in the framing of a typical wall and details at wall intersections and a window opening. In *D*, the short studs above the header and below the rough sill are called "cripple studs."

Interactive Exercise

FIGURE 5.33
The wall frame is constructed while it lies flat on the already completed floor platform. Here, studs for a partition intersection are nailed to a plate, using a pneumatic nail gun. *(Courtesy of Senco Products, Inc.)*

FIGURE 5.34
Tilting an interior partition into position. The gap in the upper top plate will receive the projecting end of the upper top plate from another partition that intersects at this point. *(Courtesy of APA–The Engineered Wood Association.)*

FIGURE 5.35
Fastening a wall to the floor platform. Horizontal blocking between studs, as seen toward the left in this photo, is installed to provide solid fastening for bathroom hardware, exterior panels, or any number of possible other items to come later. *(Courtesy of Senco Products, Inc.)*

FIGURE 5.36
Wall framing is held in place by temporary bracing until the floor framing is in place above and wall sheathing is complete, after which the frame becomes self-bracing. The outer walls of this building are framed with 2 × 6 (38 × 140 mm) studs to allow for a greater thickness of thermal insulation, whereas the interior partitions are framed with 2 × 4 (38 × 89 mm) studs. *(Photo by Joseph Iano.)*

less effective at resisting lateral forces than structural panel sheathing, and it is not suitable for use where these forces are high.

Lateral Force Resistance and Shear Walls

To a greater or lesser degree, all structures must resist the horizontally acting forces of wind and earthquake. In areas prone to very strong winds or severe earthquakes, as well as for taller wood light frame structures, special attention is given to the design of the platform frame and the detailing of its connections to ensure that it can safely withstand the effects of these *lateral forces* (Figure 5.38).

Lateral forces acting on a building can cause the structure to slide off its foundation, overturn, wrack, or suffer failures among its parts. Sliding at the top of the foundation is resisted by the anchor bolts and foundation sill plate, as described earlier in this chapter. Where the forces are high, this connection can be strengthened with thicker plates made of stronger lumber, and anchor bolts that are larger in diameter, more closely spaced, and fastened with larger washers.

FIGURE 5.37
Applying a panel of insulating foam sheathing. Because this type of sheathing is too weak to brace the frame, diagonal bracing is inserted into the outside faces of the studs at the corners of the building. Steel let-in bracing, nailed at each stud, is used in this frame and is visible just to the right of the carpenter's leg. *(Courtesy of Celotex Corporation.)*

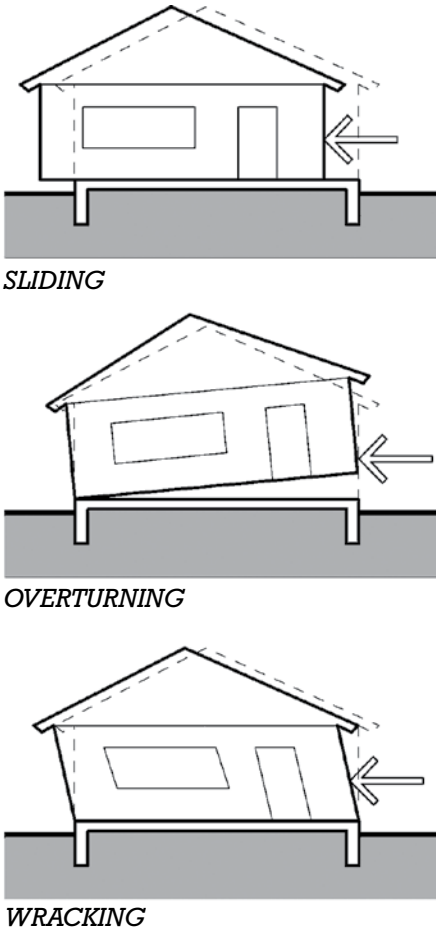


FIGURE 5.38
The lateral force resisting system of the building must resist sliding, overturning, and wracking. An additional consideration, interconnection of the parts, is discussed in the accompanying text.

To resist overturning, *hold-downs* are installed to prevent the structure from lifting off the foundation (as their name suggests). These devices may also be used higher up in the structure to prevent the upper stories or roof from separating from the portions of the structure below (Figures 5.39, 5.40, and 5.41).

A wall without sheathing or bracing has no useful resistance to *wracking*. Because the nailed connections between studs and plates are flexible, the wall can easily deform. In areas of high wind force or earthquake risk, plywood or OSB sheathing panels tightly nailed to the framing create *shear walls* (Figure 5.42) that provide the necessary rigidity. As lateral force design values increase, shear walls are made stronger by lengthening the wall, using thicker structural panels, adding a panel to the opposite side of the wall, increasing the size of nails used to attach the panels to the framing, and spacing nails more closely, especially around panel edges. Shear walls frequently also require extra studs or thicker posts at their ends to prevent localized crushing or failure where forces tend to concentrate (Figure 5.41).

Both interior and exterior walls can act as shear walls. Separate sections of wall must be arranged perpendicularly so that the structure as a whole can resist forces acting from different directions. Shear walls must also be distributed in a plan so as to ensure a reasonably balanced overall response to such forces.

Openings in shear walls, such as for doors and windows, significantly reduce their lateral force resistance. Where such openings occur, they are reinforced with blocking and strapping. Where openings take up too large a percentage of the wall area and conventional construction methods cannot provide the necessary resistance, stronger and stiffer welded steel frames or

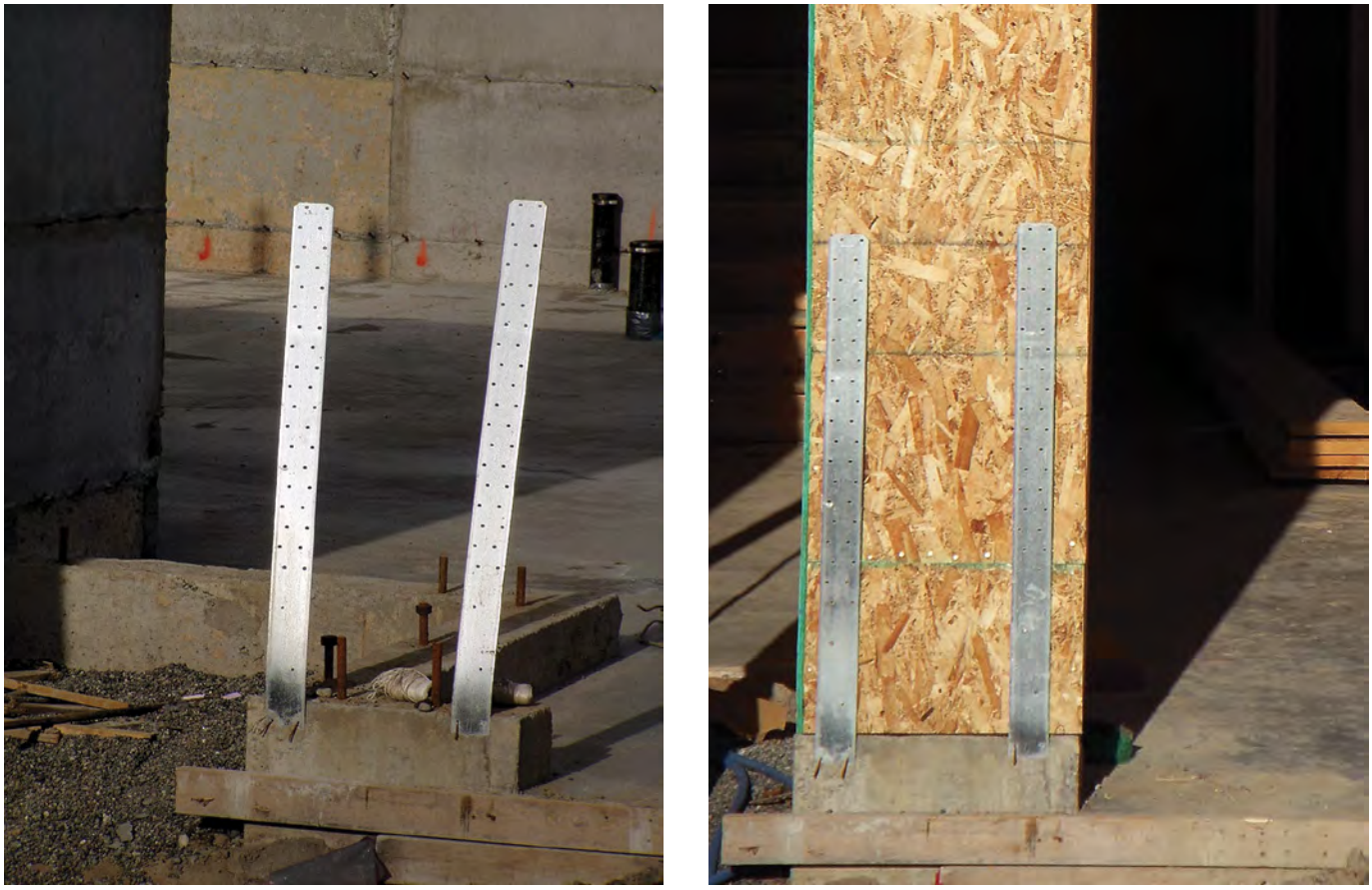


FIGURE 5.39

Strap tie hold-downs are made of galvanized steel straps with hooked or deformed ends cast into the concrete foundation wall (*left*). After the wall is framed, the exposed length of strap may be nailed directly to framing or, as seen here, nailed through the sheathing into the studs or posts behind (*right*). The number, size, and spacing of nails used to fasten the strap depend on the magnitude of the loads that must be resisted and the capacity of the wood member to hold nails without splitting. In the left image, anchor bolts cast into the top of the foundation wall that will be used to secure the sill plate in place are also visible. *(Photos by Joseph Iano.)*

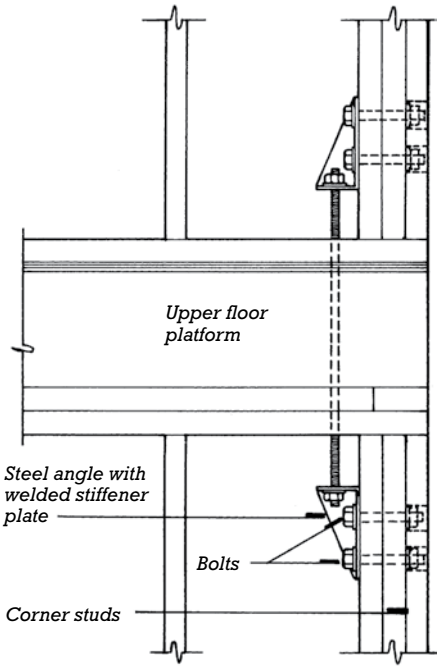


FIGURE 5.40

Hold-downs made from threaded rod and steel plate anchors can resist much greater forces than strap tie hold-downs. They may be used at each floor level to securely tie the building frame through its full height to the foundation. For the type shown here, the nuts at the ends of the threaded rods may require retightening after the first heating season to compensate for wood shrinkage, which can mean that access holes must be provided through the interior wall surfaces. Other models are made self-adjusting with the use of spring-loaded, tapered shims or other compensation mechanisms.

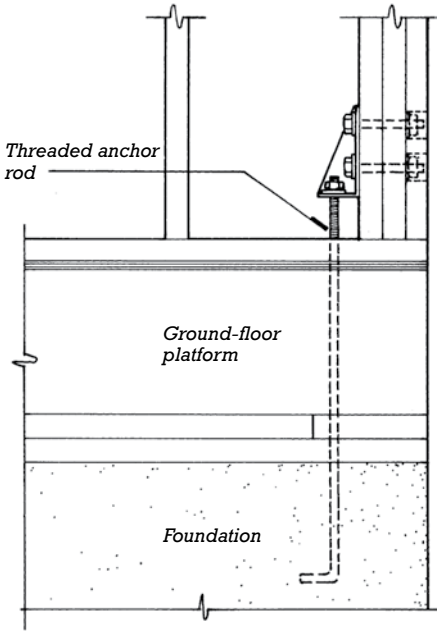


FIGURE 5.41

A heavy-duty seismic hold-down similar to that illustrated in the previous figure. The anchor rod with one end cast into the concrete foundation wall protrudes through the preservative-treated wood sill where its threaded end is bolted to the anchor. The anchor in turn is bolted to a 4 × 4 (89 × 89 mm) post with five bolts of substantial diameter. A conventional foundation anchor bolt with an oversized square washer is also partially visible to the right of the hold-down. Also note the thicker-than-normal, 3-inch nominal (64-mm) sill plate, a common feature in wood light framing designed for high seismic forces. *(Photo by Joseph Iano.)*

FIGURE 5.42
(*Top*) Shear walls for a multistory, wood light frame structure. The plywood shear panels are readily distinguishable from the surrounding yellow faced, gypsum sheathing panels. (*Bottom*) A close-up of the shear wall at the second-floor platform level. The metal clips increase the shear force transfer capacity between the top of the first-floor wall and the second-floor platform. The panel nailing pattern can be observed by the fastener weathering stains. Fasteners are more closely spaced at panel edges. The multiple rows of fasteners at the extreme left and right of the shear wall are an indication of the thicker framing members used at these locations. *(Photos by Joseph Iano.)*

factory-fabricated shear panels made of wood or steel components may be used (Figure 5.43).

In the International Building Code, the term "shear wall" is reserved for a lateral force–resisting wall designed by a professional engineer. Where the design conditions are not too severe, the code also provides for more general-purpose, preengineered, prescriptive wall designs. These so-called *braced walls*, or *braced panels*, are designed and built according to the same principles as shear walls, the difference being that no professional analysis is required. Where design forces are low, sheathing panels made from fiberboard, particle board, or even gypsum wallboard, rather than plywood or OSB, may provide adequate rigidity.

With the components necessary to resist sliding, overturning, and wracking incorporated into the building structure, it still remains necessary to ensure that the various building parts are adequately interconnected. *Collectors* (also called *drag struts*, or *drag ties*) are components that transfer lateral forces from larger areas, such as floors or roofs, to the parts of the structure that carry these forces eventually to the building foundation, such as the shear walls. For example, wall top plates typically collect lateral forces that accumulate in the floor platform above and carry these forces to the top of the nearest shear wall. Strategically located and properly fastened joists, rafters, other framing members, and (where necessary) metal strapping or solid wood blocking also perform in this way (Figure 5.44). Collectively, these components ensure continuous *load paths* so that forces acting within the various parts of the structure will be carried reliably and securely to the building foundation and surrounding soil.

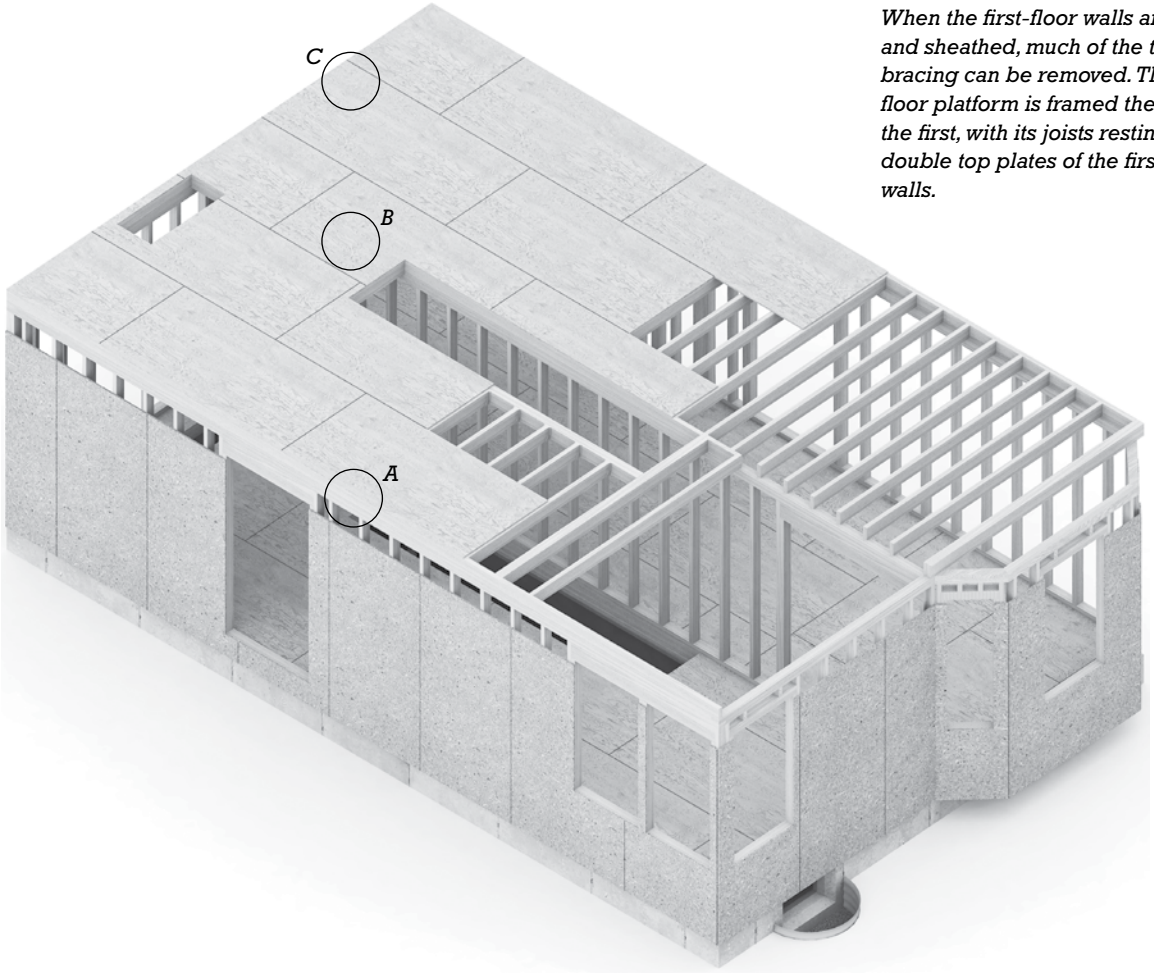
Upper-Level Floor and Wall Framing

After the first-floor platform and wall framing are complete, the process and details of floor framing followed by wall framing may continue for each additional level of the structure, as shown in Figures 5.45 through 5.50.

FIGURE 5.43
Prefabricated shear panels are especially useful where large openings in walls leave little solid area for shear wall construction, such as in garage walls. They may be made of all-wood components or, where even greater strength is required, of wood and metal, as shown here. The corrugated galvanized steel in this panel is more than 1/8 inch (3.5 mm) thick, and the panel's capacity to resist lateral forces is several times greater than that of comparable all-wood prefabricated panels. The bottom of the panel will be anchored with bolts embedded 21 inches (533 mm) or more into the concrete foundation, and the sides and top will be screw-fastened to the surrounding wood framing. Holes in the panel can accommodate wiring runs within the wall. *(Courtesy of Simpson Strong-Tie Company Inc.)*

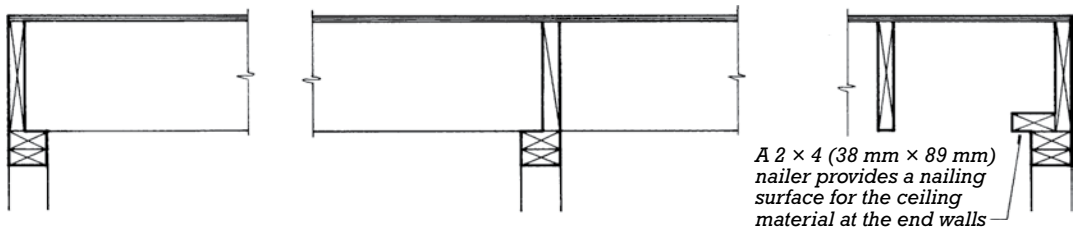
FIGURE 5.44
In addition to supporting gravity loads over the garage opening, this glulam beam acts as a collector of lateral forces in the deck framing that it supports. These forces are carried either to the narrow section of solid wall framing on the right, or via the metal strap and adjacent garage opening beam, to additional shear wall framing beyond the edge of this photograph. *(Photo by Joseph Iano.)*

When the first-floor walls are complete and sheathed, much of the temporary bracing can be removed. The second-floor platform is framed the same as the first, with its joists resting on the double top plates of the first-floor walls.



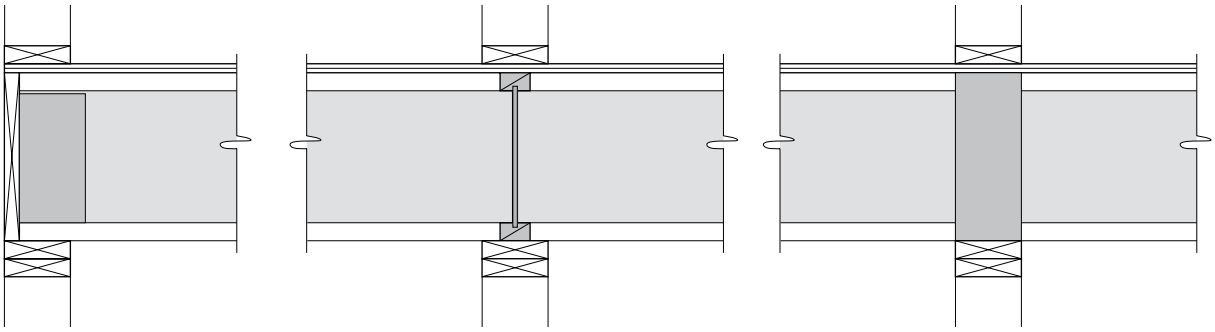
5

FIGURE 5.45
Step five in erecting a two-story platform frame building: building the upper-floor platform. The letters *A*, *B*, and *C* indicate portions of the framing that are detailed in Figures 5.46 and 5.47.



A. SIDEWALL *B. INTERIOR BEARING WALL* *C. END WALL*

FIGURE 5.46
Details of the second-floor platform, keyed to the letters in Figure 5.45. The extra piece of lumber attached to the top plate in *C* provides a nailing surface for the edge of the finish ceiling material, which is usually either gypsum board or veneer plaster base.



A. SIDEWALL WITH WEB STIFFENER

B-1. INTERIOR BEARING WITH I-JOIST BLOCKING PANEL

B-2. SQUASH BLOCK FOR CONCENTRATED LOADS

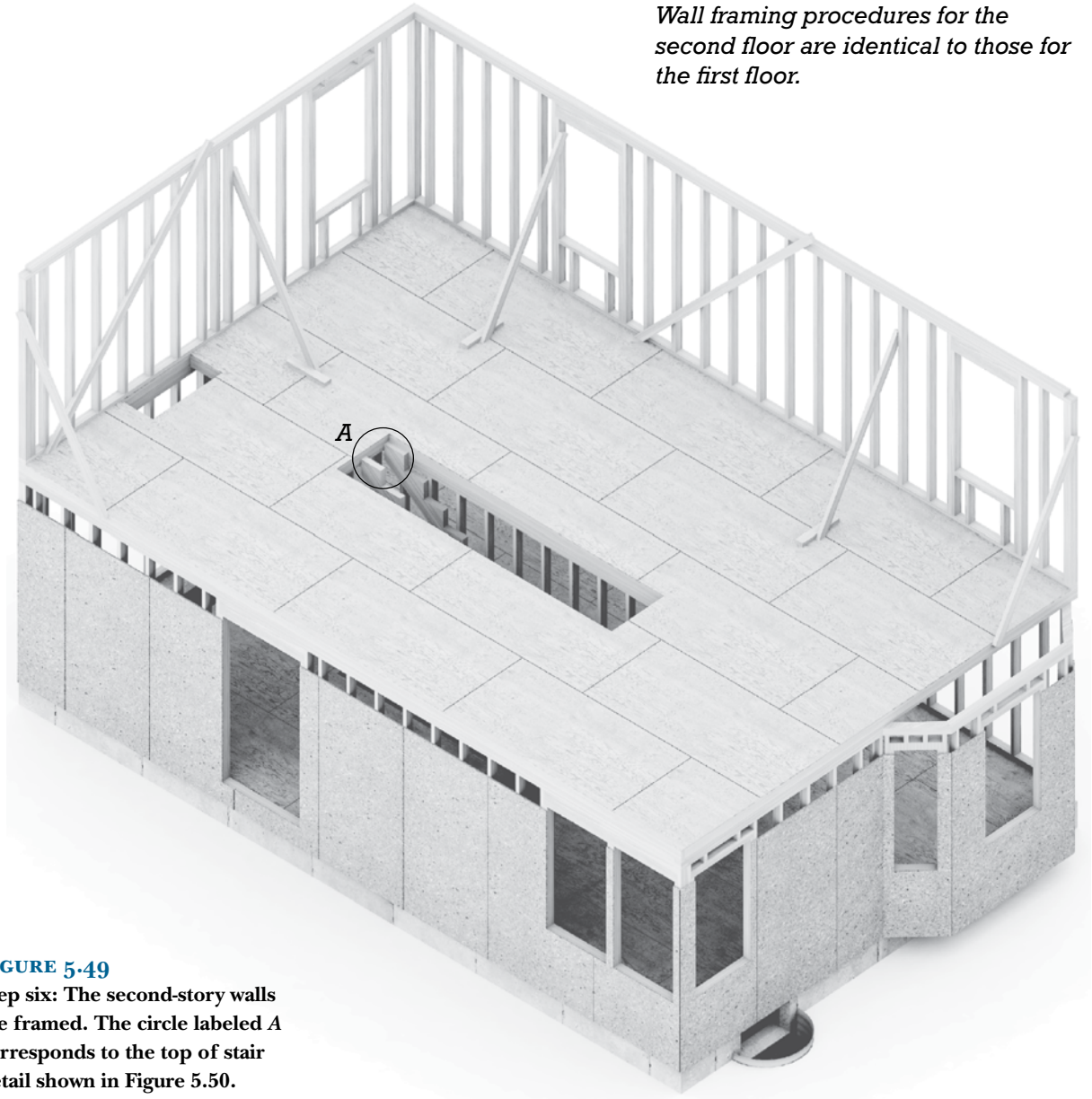
FIGURE 5.47

I-joist framing details analogous to those for solid lumber shown in Figure 5.46. For clarity, the web of the I-joist is rendered a light shade and the blocking with a darker shade. The web stiffener shown in *A* is cut slightly shorter than the height of the web of the joist and is installed so that a small space remains between the top of the blocking and the underside of the top flange. This prevents the blocking from prying the flanges apart if the I-joist itself shrinks or is compressed slightly (see also Figure 5.25). The blocking in *B-1* functions identically to the solid blocking shown in Figure 5.46*B*. A *squash block* is shown in *B-2*. This is a short section of 2-inch (38-mm) framing, installed vertically like a very short stud on either side of the I-joist. Squash blocks are used under points of concentrated load, such as under loadbearing posts or studs on either side of a large opening in a wall above. They are cut slightly longer than the full height of the joist to ensure that the loads are transmitted through the blocks and not the joist.

FIGURE 5.48

Installing upper-floor plywood combination subflooring/underlayment. The plywood panel grade is C–C Plugged. Its top (plugged) face has all surface voids filled and is lightly sanded, making it sufficiently smooth to allow carpeting to be installed directly over the subfloor without additional underlayment. The long edges of the panels have interlocking tongue-and-groove joints to prevent deflection of panel edges under heavy loads. *(Courtesy of APA–The Engineered Wood Association.)*

Wall framing procedures for the second floor are identical to those for the first floor.



6

FIGURE 5.49
Step six: The second-story walls are framed. The circle labeled *A* corresponds to the top of stair detail shown in Figure 5.50.

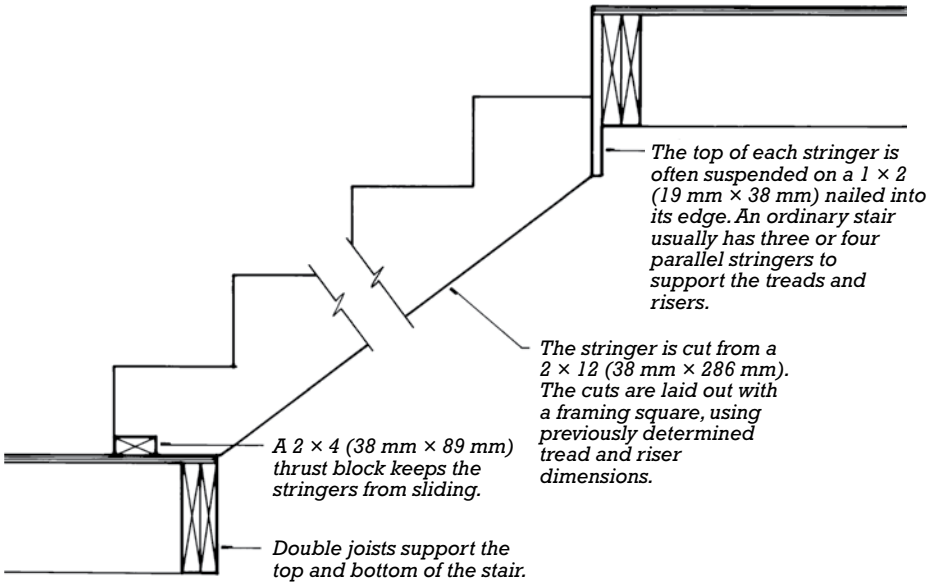


FIGURE 5.50
Interior stairways are usually framed as soon as the upper-floor platform is completed. This gives the carpenters easy up-and-down access during the remainder of the work. Temporary treads of joist scrap or plywood are nailed to the stringers. These will be replaced by finish treads after the wear and tear of construction is finished.

Roof Framing

Generic roof shapes for wood light frame buildings are shown in Figure 5.51. Simple shapes are combined into more complex arrangements suitable for covering any building plan shape and volume.

In typical gable roof framing, rafters rest on top of the uppermost story walls and are fastened to a *ridge board* where they meet at the peak of the roof. Additionally, *ceiling joists* span between the lower ends of each opposing rafter pair. In this configuration, the ceiling joists, in addition to supporting a finish ceiling, act to prevent the lower ends of the rafters from spreading outward under the weight of the roof, which would in turn cause the upper floor walls to lean outward as well. If the designer wishes to eliminate the ceiling joists and expose the sloping underside of the roof as the finished ceiling surface, either the ceiling joists must be replaced with some system of exposed horizontal *rafter ties*, or a much heavier *ridge beam* must be inserted at the ridge to help support the weight of the roof. The same considerations apply to hip roof framing as well. (See *Gable roof* and *Hip roof*, Figure 5.51.)

In some cases, the designer may wish to raise the ceiling joists or rafter ties higher within the vaulted ceiling space. However, the further the joist or tie connections move from the point where the rafters rest on top of the walls, the greater the stresses introduced into the framing system. This should be done only within the prescriptive limits of the building code or after consultation with a structural engineer. In particular, *collar ties* (Figure 5.53*A*) should not be expected to prevent spreading of rafter ends. Collar ties are located in the upper third of the rafter span and resist uplift forces in the roof (caused by high winds). However, they cannot counteract the outward spreading forces of these roof types.

As with floor framing, ceiling joists and rafters must also be protected against overturning. Requirements

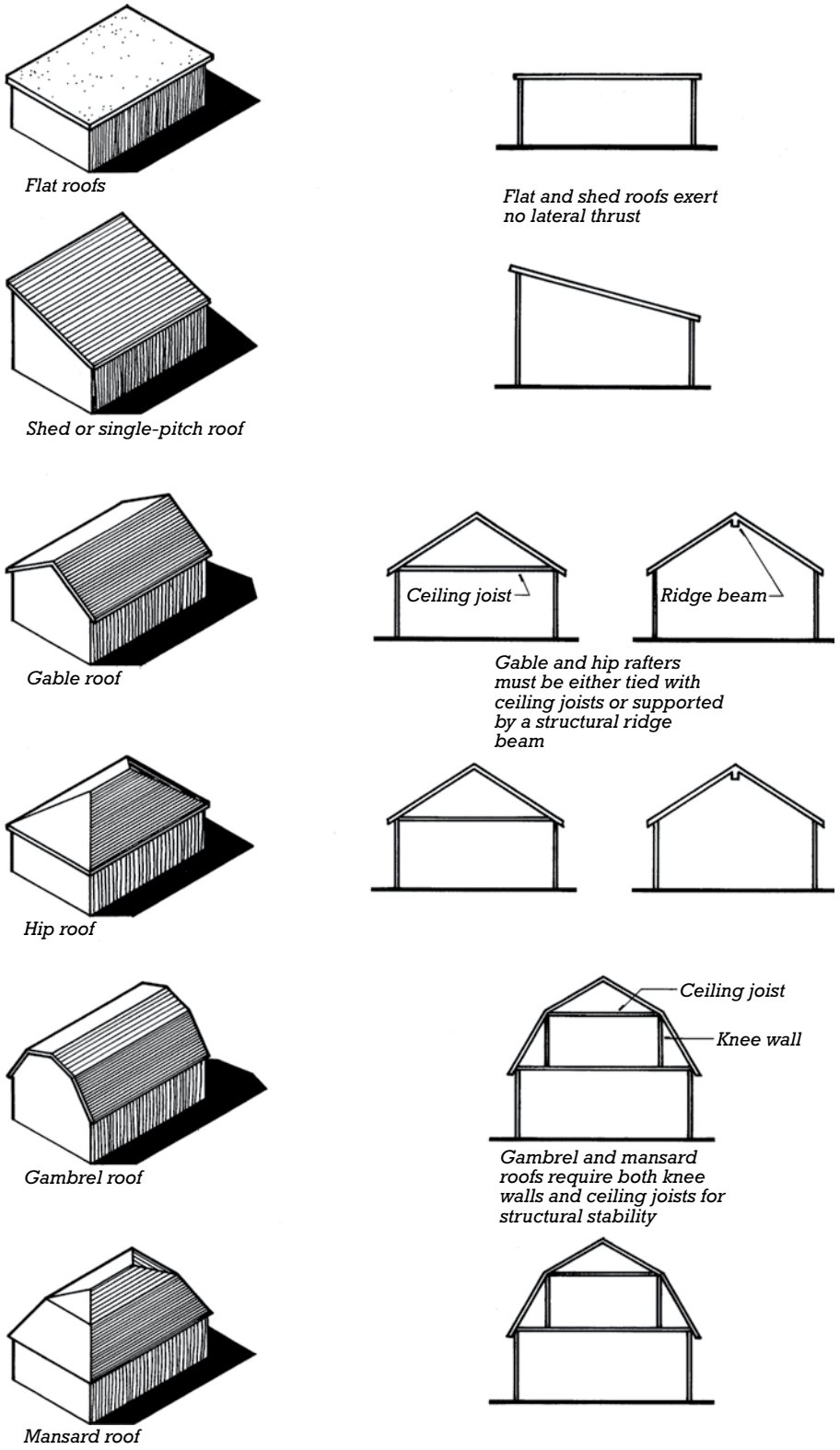
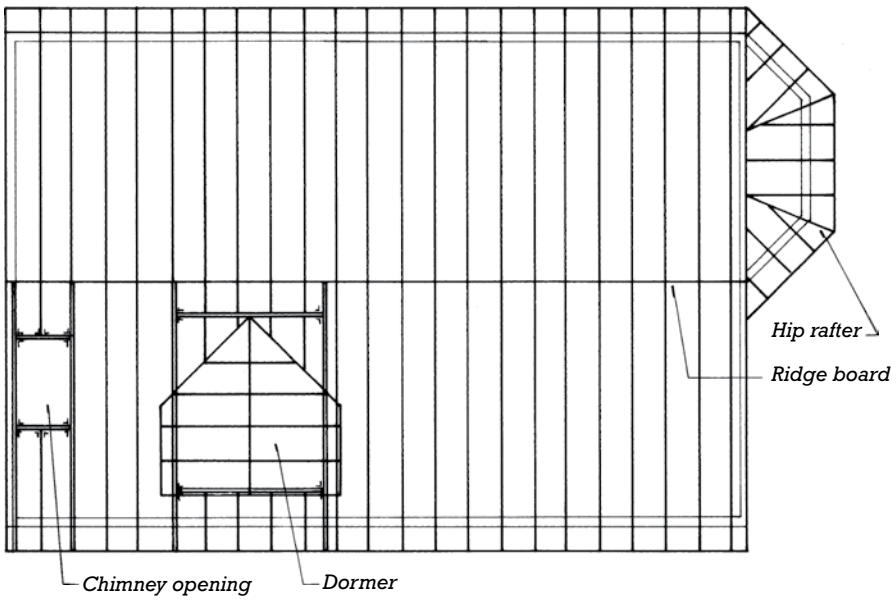


FIGURE 5.51

Basic roof shapes for wood light frame buildings. As explained in the accompanying text, when ceiling joists or rafter ties are omitted from gable or hip roof framing, heavier ridge beams must be used in place of lighter ridge boards to counteract the tendency of these framing systems to spread outward where their lower ends rest on walls.



ROOF FRAMING PLAN

FIGURE 5.52
A roof framing plan for the building illustrated in Figure 5.54. The *dormer* and chimney openings are framed with doubled header and trimmer rafters. The dormer is then built as a separate structure that is nailed to the slope of the main roof.

vary with the span, depth, and support conditions of the members and may include end nailing, blocking, bridging, or strapping, similar to those shown earlier in this chapter for floor joist framing.

Although a college graduate architect or engineer would find it difficult to use the necessary trigonometry to lay out the cuts for a rafter in a sloping roof, a skilled carpenter, without resorting to mathematics, has little problem making the layout when the *pitch* (slope) is specified as a ratio of *rise* (vertical dimension) to *run* (horizontal dimension). In the United States, pitch is usually given as inches of rise per foot (12 inches) of run. The carpenter uses these two figures on the two edges of a *framing square* to lay out the rafter, as shown in Figures 5.53 and 5.57. The actual length of the rafter is never figured, nor does it have to be, because all the measurements are made as horizontal and vertical distances with the aid of the square. Today, many carpenters prefer to do rafter layout with the aid of tables that give actual rafter lengths for various pitches and horizontal distances; these tables are stamped on the framing square itself or printed in pocket-size booklets. Or, hand-held calculators that are specially programmed to find dimensions of rafters can be used.

Hips and *valleys* introduce another level of trigonometric complexity in rafter layout, but the experienced carpenter has little difficulty even here: Again, he or she can use published tables for *hip rafters* and *valley rafters* or do the layout the traditional way, as illustrated in Figure 5.55. The head carpenter lays out only one rafter of each type by these procedures. This then becomes the *pattern rafter* from which other rafters can be traced and cut (Figure 5.58).

In areas subject to hurricanes, special care must be taken to ensure that rafters are securely attached to their supporting walls with sheet metal rafter anchors. The type, size, and spacing of the nails that attach the roof sheathing to the rafters are also closely controlled. The intent of both of these measures is to reduce the likelihood that the roof will be blown off in high winds.

The balloon frame is closely connected with the level of industrialization which had been reached in America [in the early 19th century]. Its invention practically converted building in wood from a complicated craft, practiced by skilled labor, into an industry. . . This simple and efficient construction is thoroughly adapted to the requirements of contemporary architects. . . legance and lightness [are] innate qualities of the balloon-frame skeleton.

—Sigfried Giedion, *Space, Time and Architecture: The Growth of a New Tradition*, 1967

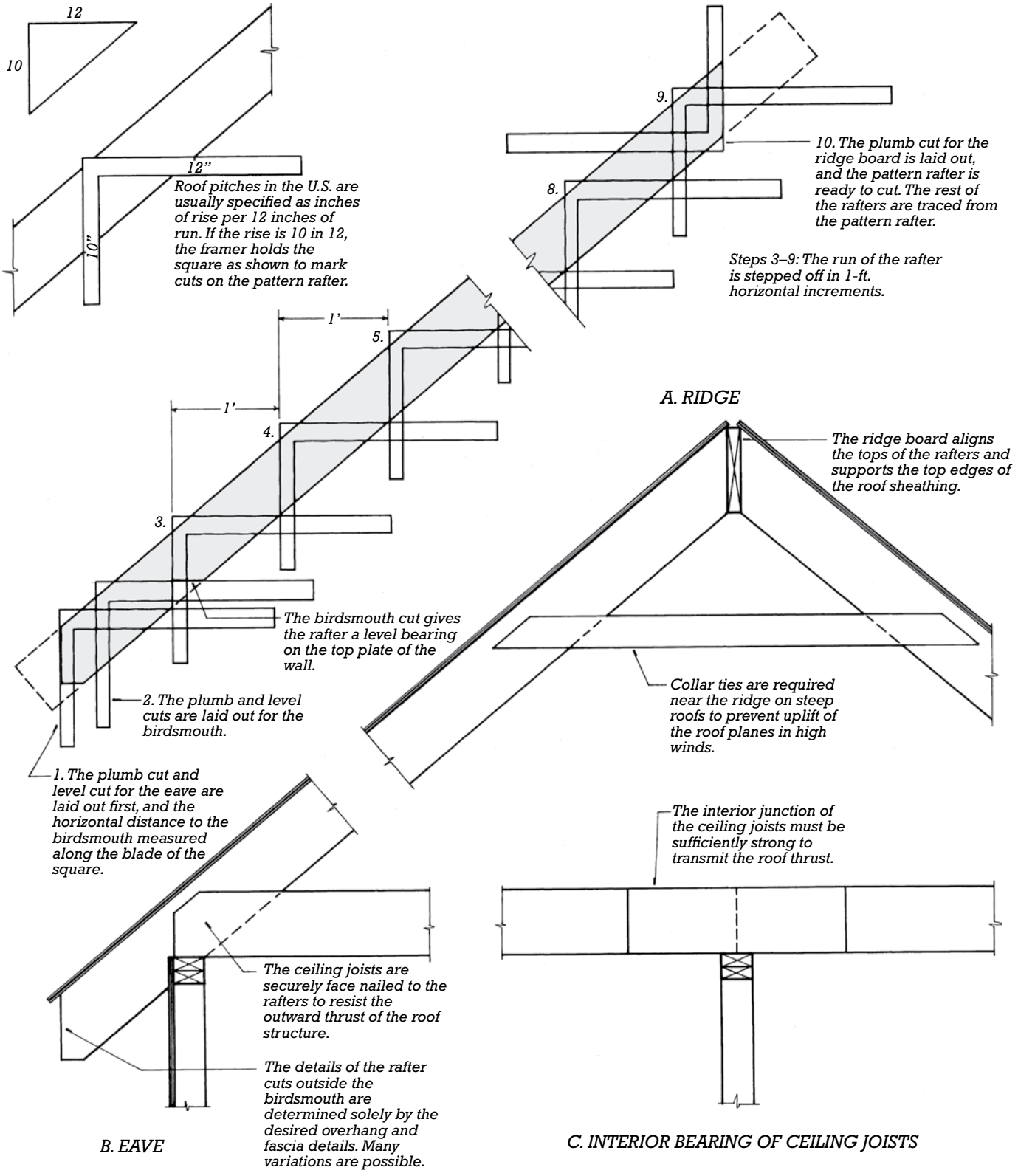
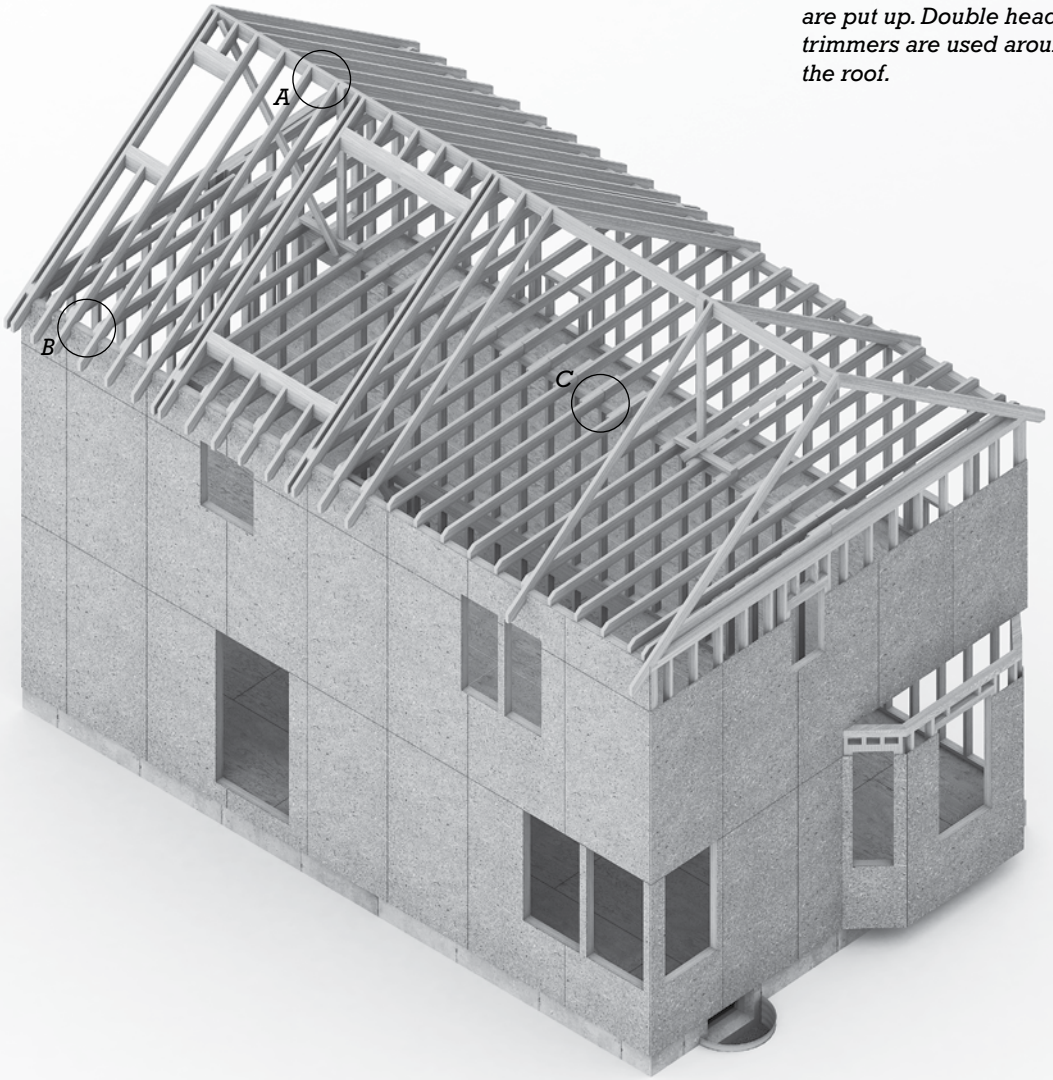


FIGURE 5.53

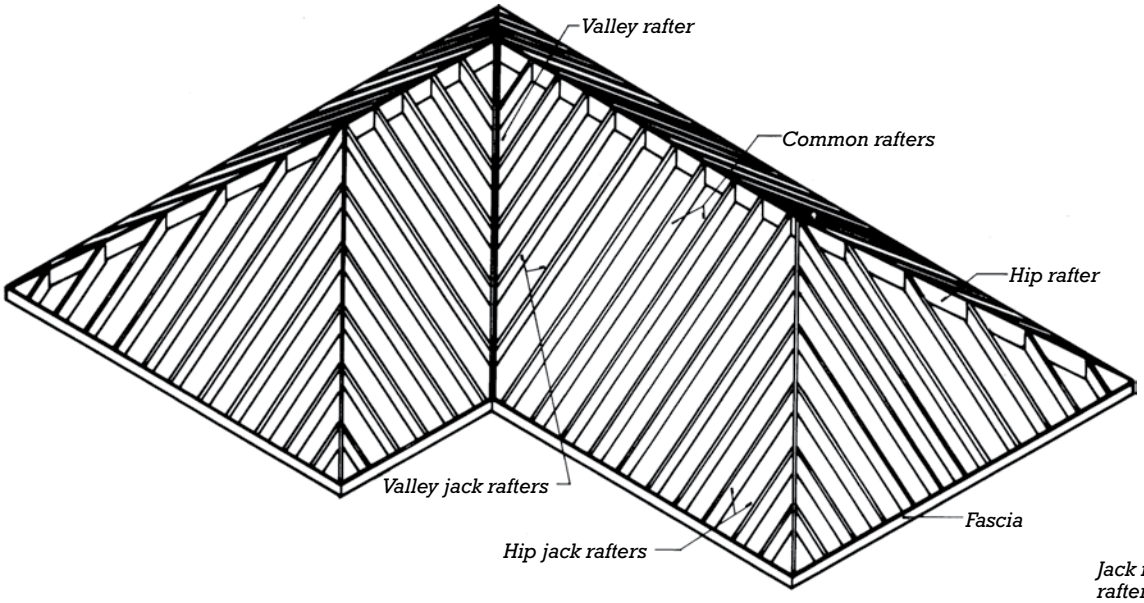
Roof framing details and procedures: The lettered details are keyed to Figure 5.54. The remainder of the page shows how a framing square is used to lay out a pattern rafter, reading from the first step at the lower end of the rafter to the last step at the top. The rafter detailed here is a *common rafter*, as distinguished from the hip, valley, and jack rafters shown in Figure 5.55.

The ceiling joists above the second floor (which also serve as the attic floor joists) are toenailed to the tops of the second-floor walls. A few rafters are then erected to support the ridge board, and the remainder of the rafters are put up. Double headers and trimmers are used around openings in the roof.

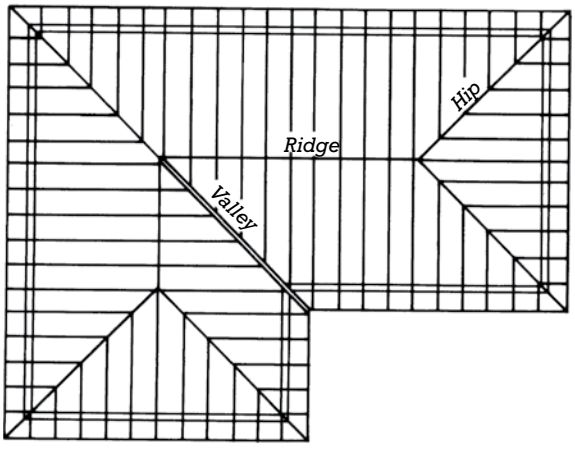


7

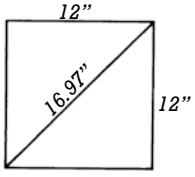
FIGURE 5.54
Step seven: framing the attic floor and roof. The outer ends of attic floor joists are not usually headed off, but instead are face nailed to the rafter pairs that overlap them.



Jack rafters are common rafters cut off at varying lengths to meet a hip or valley rafter. The jacks meet the hip or valley at a compound angle that is easily laid out with a framing square.



FRAMING PLAN



The diagonal of a 12" square is 16.97", or very nearly 17". In laying out a hip or valley rafter, the framer simply aligns the framing square to the rise per foot of a common rafter on the tongue and 17" rather than 12" on the blade. The marking and stepping-off operations are otherwise identical to those for a common rafter.

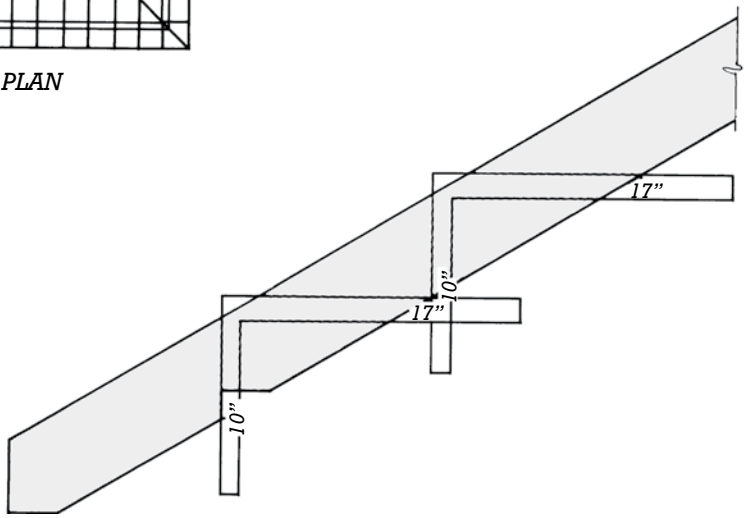
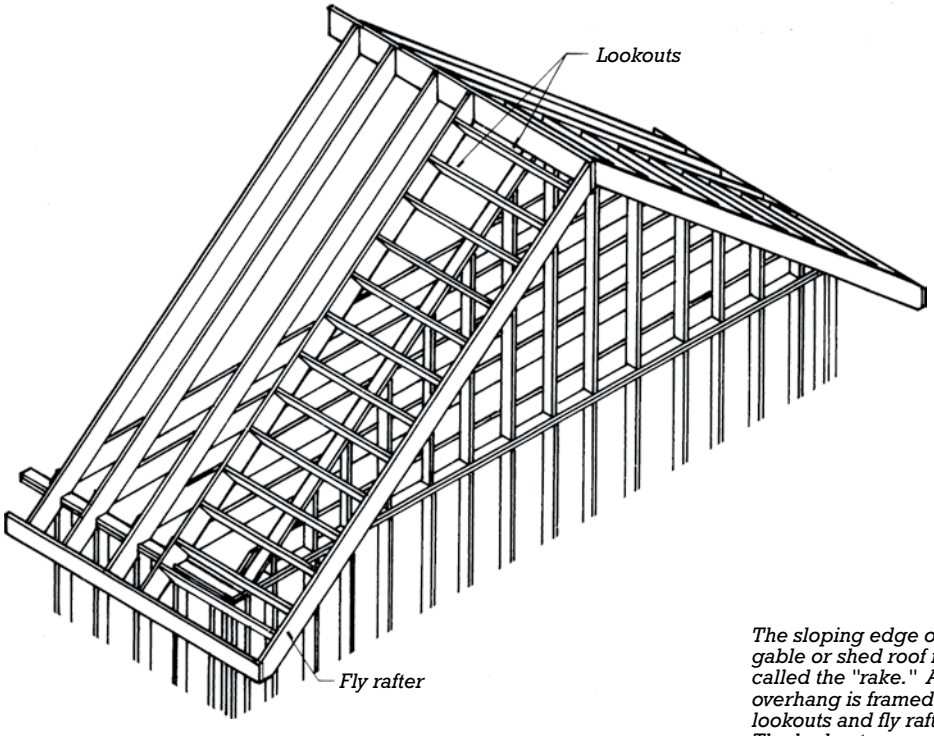


FIGURE 5.55
Framing for a hip roof. The difficult geometric problem of laying out the diagonal hip rafter is solved easily by using the framing square in the manner shown. Toward the bottom of the rafter shown in the lower part of this figure is a *birdsmouth cut*, an angled notch in the rafter that allows the rafter to seat securely on the top plate of the wall.



The sloping edge of a gable or shed roof is called the "rake." A rake overhang is framed with lookouts and fly rafters. The lookouts are supported by a top plate over the gable end studs.

FIGURE 5.56
Framing for an overhanging *rake*.

FIGURE 5.57
A framing square being used to mark rafter cuts. The run of the roof, 12 inches, is aligned with the edge of the rafter on the blade (the wider leg) of a square, and the rise, 7 inches in this case, is aligned on the tongue (the narrower leg) of the square. A pencil line along the tongue will be perfectly vertical (a *plumb cut*) when the rafter is installed in the roof, and one along the blade will be horizontal (a *level cut*). True horizontal and vertical distances can be measured on the blade and tongue, respectively. The layout of these types of cuts can also be seen in Figures 5.53 and 5.55. *(Photo by Edward Allen.)*

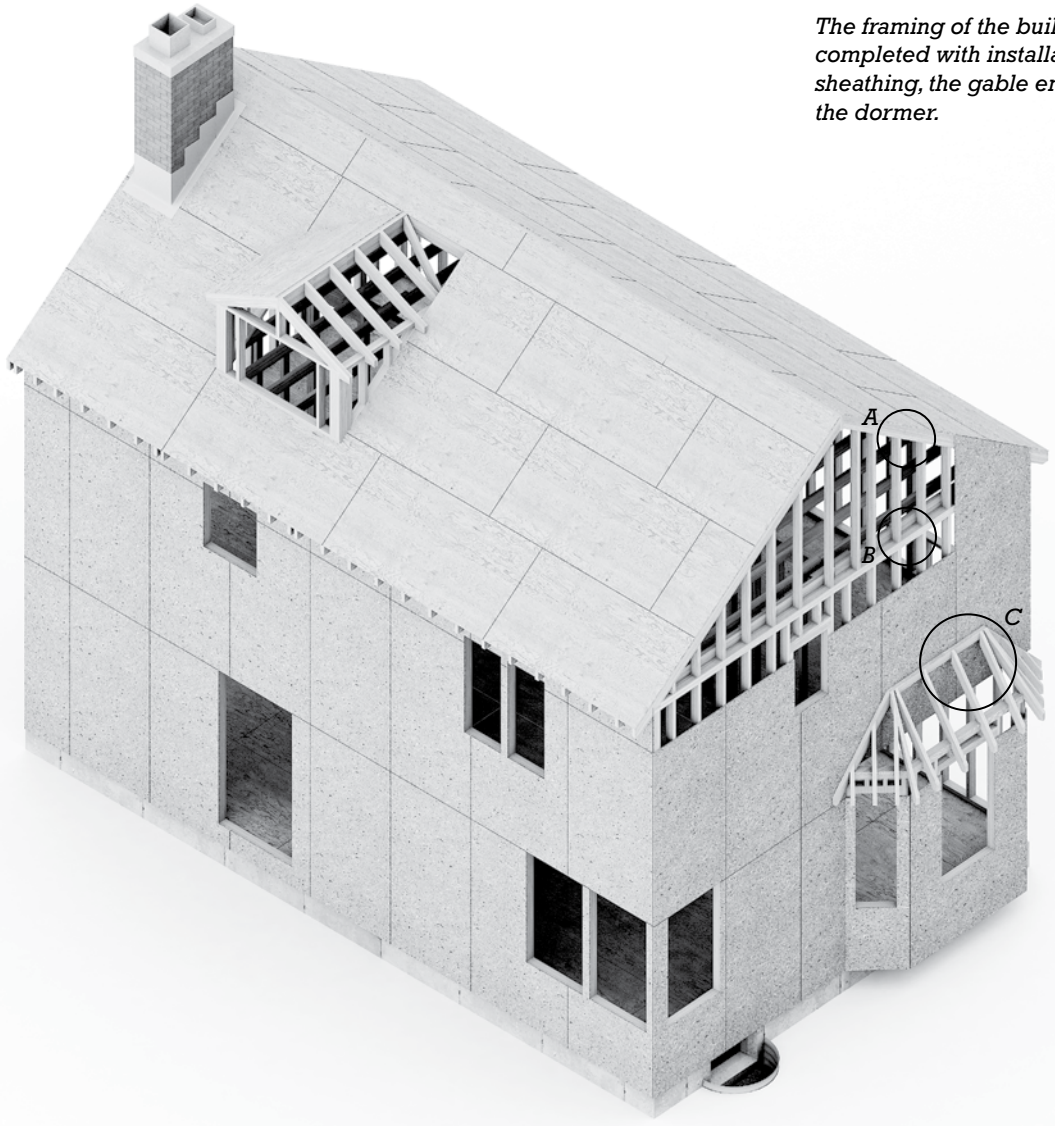
FIGURE 5.58
Tracing a pattern rafter to mark cuts for the rest of the rafters. The corner of the building behind the carpenters has let-in corner braces on both floors, and most of the rafters are already installed. *(Courtesy of Southern Forest Products Association.)*

FIGURE 5.59
I-joists may be used as rafter material instead of solid lumber. *(Courtesy of Trus Joist MacMillan.)*

FIGURE 5.60
Applying plywood roof sheathing to a half-hipped roof. Blocking between rafters at the wall line (far left in the photo) has been drilled with large holes for attic ventilation. The line of horizontal blocking between studs is to support the edges of plywood siding panels applied in a horizontal orientation. *(Courtesy of APA–The Engineered Wood Association.)*

FIGURE 5.61
Fastening roof sheathing with a pneumatic nail gun. *(Courtesy of Senco Products, Inc.)*

The framing of the building is completed with installation of the roof sheathing, the gable end walls, and the dormer.



8

Figure 5.62
Step eight: The sheathed frame is completed.

Figure 5.63
A wood light frame structure fully sheathed with plywood structural panels. Installation of wood trim around the edges of the roof has also begun. *(Photo by Joseph Iano.)*

Variations on Wood Light Frame Construction

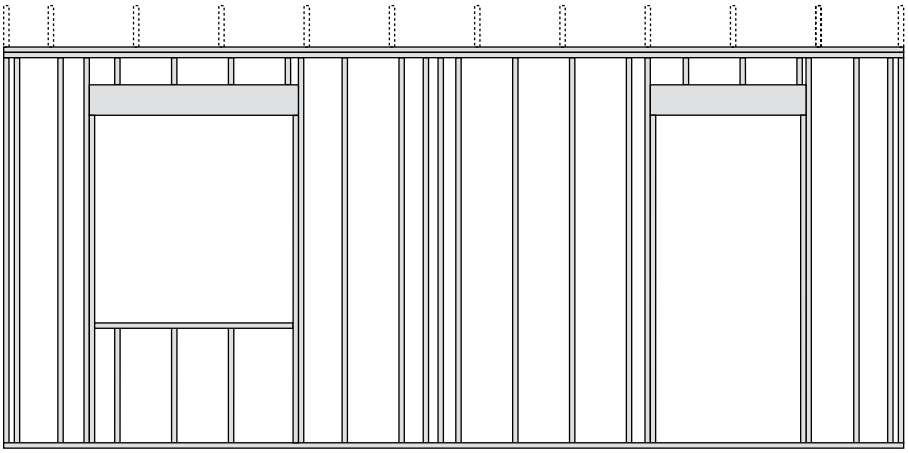
Framing for Increased Thermal Efficiency

The 2 × 4 (38 × 89 mm) has been the standard-size wall stud since light framing was invented. More recently, however, the desire for greater conservation of fuel for heating and cooling has led to energy code requirements for more thermal insulation than can be inserted in the cavities of a wall framed with members only 3½ inches (89 mm) deep. One solution is to frame walls with 2 × 6 (38 × 140 mm) studs, usually at a spacing of 24 inches (610 mm), creating an insulation cavity 5½ inches (140 mm) deep. Alternatively, 2 × 4-framed walls may be covered either inside or out with insulating plastic foam or mineral wood board sheathing, thus reaching an insulation value about the same as that of a conventionally insulated 2 × 6-framed wall. In very cold climates or where greater energy efficiency is desired, even more heavily insulated wall may be constructed. Some of these methods are illustrated in Figures 7.17 and 7.18.

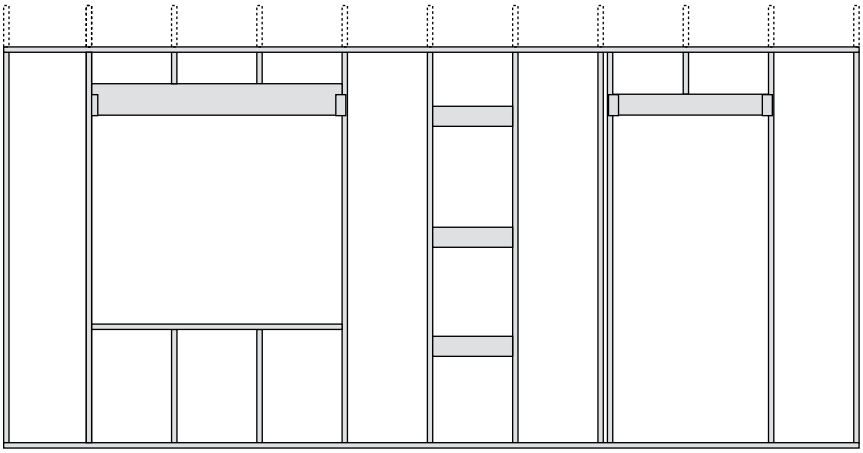
Framing for Optimal Lumber Usage

Using *advanced framing techniques* (also called *optimum value engineering*), redundant or structurally superfluous wood members are minimized, thereby reducing the amount of lumber needed to construct the frame and, once the frame is insulated, increasing its thermal efficiency (Figure 5.64). A variety of techniques may be used, including:

- *Spacing framing members at 24 inches (610 mm) rather than 16 inches (406 mm) o.c.* Wider spacing of framing members reduces the amount of lumber



A. Conventional wall framing with studs @ 16 o.c.



B. Wall framed with advanced framing techniques

FIGURE 5.64
Comparison of walls framed with conventional and advanced techniques. Wall *A* is framed as explained in Figure 5.32. Studs are spaced at 16 inches (406 mm) o.c., the layout of the wall and its openings is not coordinated with the framing module, and standard details are used for corners, openings, and other features. In wall *B*, studs are spaced at 24 inches (610 mm) o.c., the length of the wall and the location and size of its openings have been coordinated to the greatest extent possible with the 24-inch module, and redundant framing members have been eliminated. Note that with the single top plate, floor joists or roof rafters (shown dashed in these figures) bearing on wall *B* must fall directly over studs below. The total length of framing lumber used in wall *B* is half that required for wall *A*. Though only a foot and a half shorter in length, wall *B* also can be sheathed with five standard-sized sheathing panels, whereas wall *A* requires six. Even if wall *A* is constructed of 2 × 4 studs and wall *B* is constructed of 2 × 6 studs, the overall savings in materials and reduction in waste in wall *B* are substantial.

required. In exterior walls, thermal efficiency is improved in comparison to walls framed with more closely spaced members by the reduction in thermal bridging that occurs at the studs.

- *Designing to a 24-inch (610-mm) module.* When the outside dimensions of a framed structure conform to a 24-inch module, sheathing panel waste is minimized. Planning rough opening sizes and locations in floors, walls, and roofs to conform, where possible, to this module can reduce waste even further. Designing to modular dimensions also reduces wastage of interior wallboard.
- *Using single top plates in all walls, both bearing and nonbearing.* In the case of bearing walls, this requires floor or roof framing members to align directly over studs in the walls that support them.
- *Minimizing other unneeded framing members.* Avoid headers over openings in nonbearing walls, as they are not needed; in bearing walls, use headers only as deep as required for the loads and span. Where corner studs serve only to provide nailing surfaces or support for wallboard, use other, less wasteful blocking techniques or metal clips designed for this purpose instead. Replace jack studs supporting headers at window and door openings with metal hangers; eliminate unneeded cripple studs under rough sills. All of these techniques save lumber and, in exterior walls, increase energy efficiency by reducing thermal bridging through solid framing.
- *Eliminating unneeded plywood and OSB wall sheathing.* Where let-in bracing is structurally adequate for lateral force resistance, eliminate structural panel wall sheathing entirely and cover walls with insulating sheathing for better thermal efficiency. Where structural panels are required, use the minimum number of panels necessary.

Advanced framing techniques rely on unconventional framing methods and greatly reduce redundancy in the building frame. For these reasons, they should not be used

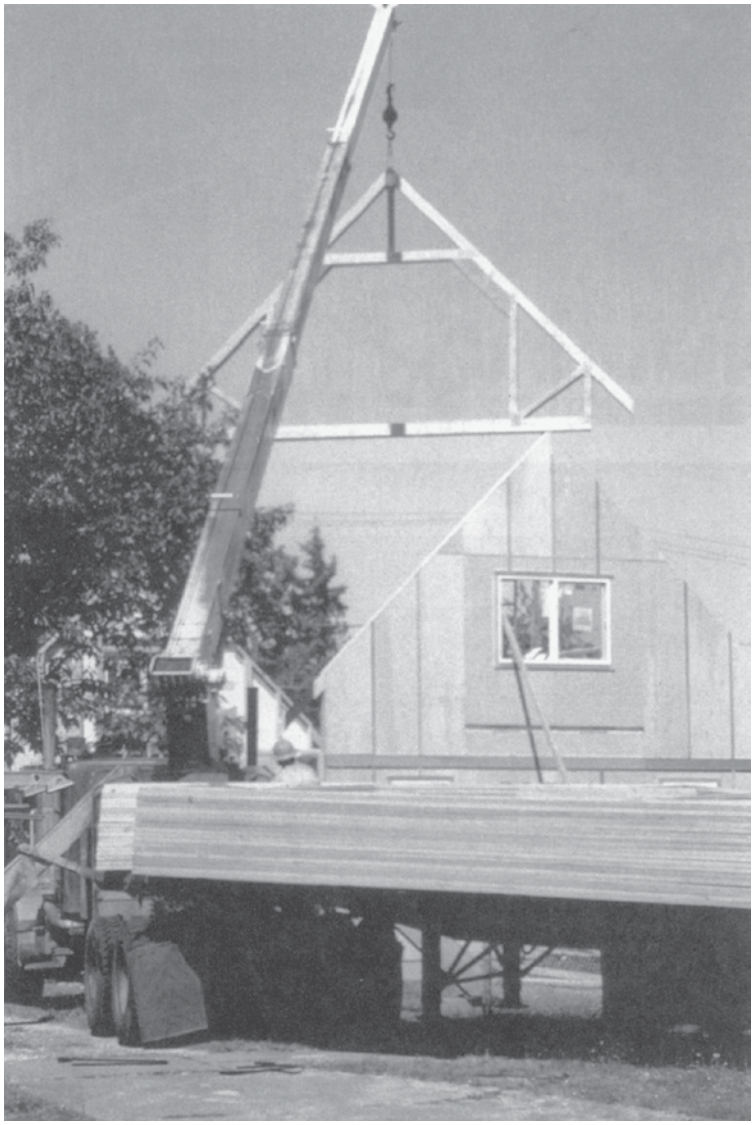


FIGURE 5.65
Roof trusses are typically lifted to the roof by a boom mounted on the delivery truck. This is one of a series of identical attic trusses that will frame a habitable space under the roof. *(Photo by Rob Thallon.)*

without guidance from a structural engineer or other qualified design professional, and special review and approval from local building authorities may be required. Nevertheless, where these techniques are used, significant benefits can be realized. According to the National Association of Home Builders Partnership for Advancing Technology in Housing, advanced framing techniques can reduce the amount of lumber used in a wood light frame structure by up to 19 percent and improve the energy efficiency of the insulated structure by as much as 30 percent.

Prefabricated Framing Assemblies

Roof trusses, and to a lesser extent *floor trusses*, are used in platform frame buildings because of their speed of erection, economy of material usage, and long spans. Though some floor trusses are light enough to be lifted and installed by two carpenters, most truss assemblies are erected with the aid of a small crane that often is attached to the truck on which the trusses are delivered (Figure 5.65). Roof trusses are particularly slender in proportion, usually only 1½ inches (38 mm) thick, and are capable of spanning 24 to 32 feet (7.5 to 10 m). They must be temporarily braced during construction (to prevent buckling or the domino-like collapse of all the trusses) until they are adequately secured permanently by the application of internal bracing, roof sheathing panels, and interior finishes (Figure 5.66). Panelized walls—framed and sheathed sections of wall assembled in the factory and delivered to the construction site ready to be erected—are used mostly by larger, high-volume builders who construct hundreds or thousands of houses per year.

Figure 5.66
A roof framed with prefabricated trusses. Approximately midway up the upper chords of the trusses temporary strapping ties the trusses to one another for bracing. Other diagonal bracing, not visible in this photograph, ties the trusses to floor or ceiling framing to prevent the entire row from collectively tipping sideways. *(Photo by Joseph Iano.)*

Preliminary Design of Wood Light Frame Structures

Estimate the depth of **wood rafters** on the basis of the horizontal (not slope) distance from the outside wall of the building to the ridge board in a gable or hip roof and the horizontal distance between supports in a shed roof. A 2 × 4 rafter spans approximately 7 feet (2.1 m); a 2 × 6, 10 feet (3.0 m); a 2 × 8, 14 feet (4.3 m); and a 2 × 10, 17 feet (5.2 m).

The depth of **wood light roof trusses** is usually based on the desired roof pitch. A typical depth is one-quarter of the width of the building, which corresponds to a 6:12 pitch in a gable truss. Trusses are generally spaced 24 inches (600 mm) o.c. and can span up to approximately 65 feet (20 m).

Estimate the depth of **wood floor joists** as follows: 2 × 6 joists span up to 9 feet (2.7 m), 2 × 8 joists 11 feet (3.4 m), 2 × 10 joists 14 feet (4.3 m), and 2 × 12 joists 17 feet (5.2 m).

Estimate the depth of manufactured **wood I-joists** as follows: 9½-inch (240-mm) joists span 16 feet (4.9 m), 11⅞-inch (300-mm) joists span 19 feet (5.8 m), 14-inch (360-mm) joists span 23 feet (7.0 m), and 16-inch (400-mm) joists span 25 feet (7.6 m).

Estimate the depth of **wood floor trusses** as ⅛ of their span. Typical depths of floor trusses range from 12 to 28 inches (305–710 mm) in 2-inch (51-mm) increments.

2 × 4 **wood studs** 24 inches (600 mm) o.c. can support attic and roof loads only. Either 2 × 4 studs 16 inches (400 mm) o.c. or 2 × 6 studs 24 inches o.c. can support one floor plus attic and roof. 2 × 6 studs 16 inches o.c. can support two floors plus attic and roof.

Framing members in light frame buildings are usually spaced either 16 or 24 inches (400 or 600 mm) o.c. For actual sizes of dimension lumber in both conventional and metric units, see Figures 3.21 and 3.22.

These approximations are valid only for purposes of preliminary building layout and must not be used to select final member sizes. They apply to the normal range of building occupancies, such as residential, office, commercial, and institutional buildings. For manufacturing and storage buildings, use somewhat larger members.

For more comprehensive information on preliminary selection and layout of a structural system and sizing of structural members, see Edward Allen and Joseph Iano, *The Architect's Studio Companion* (6th ed.), Hoboken, NJ, John Wiley & Sons, 2017.

Wood Light Frame Construction and the Building Codes

Wood light frame is a combustible construction system, permitted in Types III and V construction of the International Building Code (Figure 1.5). Most frequently, it is classified as Type V-B, meaning it is constructed without added fire protection.

As shown in the table in Figure 1.4, buildings of many occupancy classifications can be constructed with Type V-B construction, but with relatively strict restrictions on height and floor area. For example, an unsprinklered commercial office building, Occupancy B Business, of Type V-B construction may be two stories in height and 9000 square feet (835 m^2) in area per floor. However, if one hour of fire protection is added to the structure, making it Type V-A construction, it may be three stories in height and twice as large in area. (Recall also that allowable floor areas in this table can in many circumstances be increased further by

installing an automatic fire suppression sprinkler system.)

Wood light frame construction is also regulated under the International Residential Code for One- and Two-Family Dwellings when used to construct single- or two-family homes, or residential townhouses, not more than three stories in height. This code provides extensive prescriptive guidance on the structural design, life-safety, durability, habitability, and other aspects of residential building and is the model code under which most U.S. single- and two-family homes are built.

Generally, fire-resistance-rated construction is not required in the International Residential Code, regardless of building area, except to protect against the spread of fire between dwellings. Separations between dwelling units in two-family structures, construction close to property lines, and party walls separating townhouses are required to have fire resistance ratings ranging from ½ hour to 2 hours. For example, walls separating townhouses must have a 1- or 2-hour rating, depending on the manner in which they are constructed and whether fire sprinkler systems are present. These walls must extend from the foundation through the roof and be constructed so that the fire separation remains intact even if the construction on either side is destroyed by fire. A traditional such party wall is made of brick or concrete masonry, but lighter, less expensive systems

FIGURE 5.67
This proprietary fire wall consists of light gauge metal framing, noncombustible insulation, and gypsum board. The metal framing is attached to the wood structure on either side with special clips (not shown here) that break off if the wood structure burns through and collapses, leaving the wall supported by the undamaged clips on the adjacent building. *(Photo of area separation wall supplied by Gold Bond Building Products, Charlotte, NC.)*

FIGURE 5.68
This townhouse has collapsed completely as the result of an intense fire, but the houses on either side, protected by fire walls of the type illustrated in Figure 5.67, are essentially undamaged. *(Photo of area separation wall supplied by Gold Bond Building Products, Charlotte, NC.)*

FIGURE 5.69
This mixed-use building is being constructed of cast-in-place concrete up to the first floor above grade and of wood light framing above. The building code permits such *podium structures* to be larger in size than those constructed of wood exclusively. *(Photo by Joseph Iano.)*

using metal framing and gypsum board may also be used (Figures 5.67 and 5.68).

Though platform frame construction is the least fire-resistive of all construction types, building code limits placed on it are sufficiently flexible to allow its use for a diverse range of building uses (Figure 5.69). Furthermore, its economies are such that most building owners will choose platform frame construction over more fire-resistant construction types if given the opportunity. And, despite the vulnerability to fire of wood light frame buildings, the comprehensive life-safety requirements of contemporary building codes ensure that they are safe places for their occupants.

Uniqueness of Wood Light Frame Construction

Wood light framing is popular because it is a flexible and economical way of constructing buildings (Figures 5.70 through 5.74). Its flexibility

FIGURE 5.70
The W. G. Low house, built in Bristol, Rhode Island, in 1887 to the design of architects McKim, Mead, and White, illustrates both the essential simplicity of wood light framing and the complexity of which it is capable. *(Photo by Wayne Andrews.)*

stems from the ease with which carpenters using ordinary tools can create buildings of astonishing variety and complexity. Its economy can be attributed in part to the relatively unprocessed nature of the materials from which it is made, and in part to mass-market competition among suppliers of components and materials and local competition among small builders.

Platform framing is the one truly complete and open system of construction that we have. It incorporates structure, enclosure, thermal insulation, mechanical installations, and finishes into a single constructional concept. Thousands of products are made to fit it: competing brands of windows and doors; interior and exterior finish materials; and electrical, plumbing, and heating products. For better or worse, it can be dressed up to look like a building of wood or of masonry in any architectural style from any era of history. Architects have failed to exhaust its formal possibilities, and engineers have failed to invent a new environmental control system that it cannot assimilate. Wood light frame construction can be used to construct the cheapest and most mundane buildings. Yet, one can look to the best examples of the Carpenter Gothic, Queen Anne, and Shingle-style buildings of the 19th century, or the Bay Region and Modern styles of more recent times, to realize that wood light framing also gives the designer the freedom to make a finely crafted building that nurtures life and elevates the spirit.

FIGURE 5.71
In the late 19th century, the sticklike qualities of wood light framing often found expression in the exterior ornamentation of houses. *(Photo by Edward Allen.)*

FIGURE 5.72
Light wood frame construction is used to build the vast majority of housing in North America. It remains to this day the most affordable and versatile construction system for buildings of this type. *(Project: New Holly Phase I, by Weinstein A\|U Architects & Planners. Photo by Joseph Iano.)*

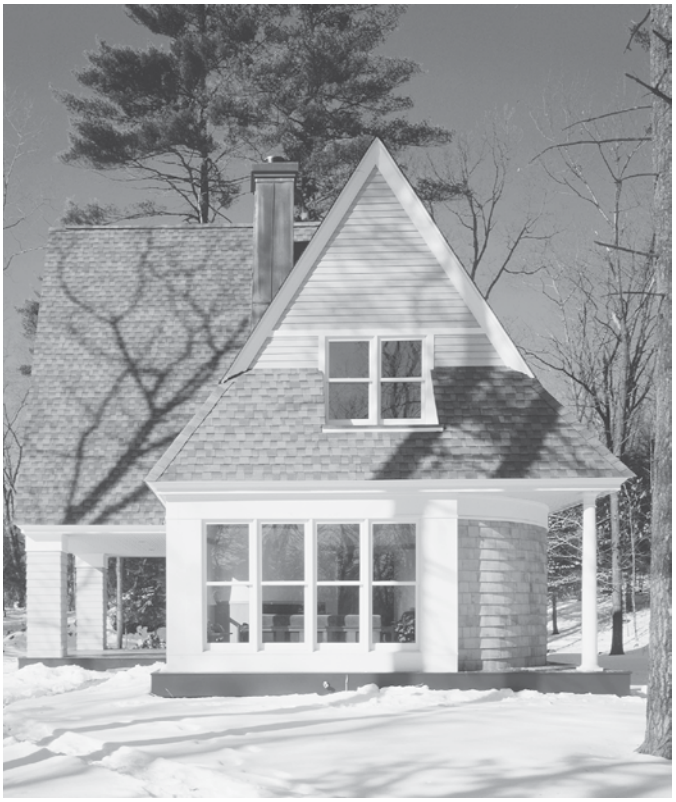


FIGURE 5.73
In this contemporary New England cottage, designer Dennis Wedlick has exploited the sculptural possibilities of platform framing. *(Photo: © Michael Moran.)*

FIGURE 5.74
The Thorncrown Chapel in Eureka Springs, Arkansas, designed by Fay Jones and Associates, Architects, combines large areas of glass with special framing details to create a richly inspiring space. To avoid damage to the sylvan site, all materials were carried in by hand rather than on trucks. Thus, all framing was done with nominal 2-inch (38-mm) lumber rather than heavy timbers. *(Photo by Christopher Lark, courtesy of American Wood Council.)*

MasterFormat Sections for Light Wood Frame Construction	
06 10 00	ROUGH FRAMING
06 14 00	TREATED WOOD FOUNDATIONS

Key Terms

wood light frame construction
balloon frame
joist
stud
rafter
fireblocking
platform frame
sheathing
rim board, band joist
subfloor
sole plate, bottom plate
top plate
ridge board
header
trimmer
sill
trimmer stud
o.c., on center
batter board
permanent wood foundation
framing plan
section detail
architectural floor plan
exterior elevation
building section
interior elevation
rough carpentry
foundation sill plate, mudsill
sill seal, sill gasket
termite shield
bridging
web blocking
jack stud
king stud
rough sill
cripple stud
let-in diagonal bracing
lateral force
hold-down
wracking
shear wall
braced wall, braced panel
collector, drag strut, drag tie
load path
squash block
ridge board
ceiling joist
rafter tie
ridge beam
collar tie
pitch
rise
run
framing square
dormer
common rafter
hip
valley
hip rafter
valley rafter
pattern rafter
birdsmouth cut
valley jack rafter
hip jack rafter
fascia
rake
plumb cut
level cut
advanced framing technique, optimum value engineering
roof truss
floor truss
podium structure

Review Questions

1. Draw a series of simple section drawings to illustrate the procedure for erecting a platform frame building, starting with the foundation and continuing with the ground floor, the ground-floor walls; the second floor, the second-floor walls; and the roof. Do not show details of connections, but simply represent each plane of framing in your section drawing.

2. Draw from memory the standard detail sections for a two-story platform frame dwelling. *Hint*: The easiest way to draw a detail section is to draw the pieces in the order in which they are put in place during construction. If your simple drawings from Question 1 are correct, and if you follow this procedure, you will not find this question too difficult.

3. What are the differences between balloon framing and platform framing? What are the advantages and disadvantages of each? Why has platform framing become the method of choice?

4. Why is less fireblocking required in platform framing in comparison to balloon framing?

5. Why is a steel beam or glue-laminated wood beam preferred to a solid wood beam for supporting floor joists at the foundation level?

6. How is a platform frame building braced against wind and earthquake forces?

7. Light framing of wood is highly combustible. In what different ways does a typical building code take this fact into account?

Exercises

1. Visit a building site where a wood platform frame is being constructed. Compare the details that you see on the site with the ones shown in this chapter. Ask the carpenters about the procedures you see them using. When their details differ from the ones illustrated, make up your own mind about which is better and why.

2. Develop floor framing and roof framing plans for a building you are designing. Estimate the approximate sizes of the joists and rafters using the rules of thumb provided in this chapter.

3. Make thumbnail sketches of 20 or more different ways of covering an L-shaped building with combinations of sloping roofs. Start with the simple ones (a single shed, two intersecting sheds, two intersecting gables) and work up to the more elaborate ones. Note how the varying roof heights of some schemes could provide room for a partial second-story loft or for high spaces with clerestory windows. How many ways do you think there are of covering an L-shaped building with sloping roofs? Look around as you travel through areas with wood frame buildings, especially older areas, and see how many ways designers and framers have roofed simple buildings in the past. Build up a collection of sketches of ingenious combinations of sloping roof forms.

4. Build a scale model of a platform frame from basswood or pine, reproducing accurately all its details, as a means of becoming thoroughly familiar with them. Better yet, build a small frame building for someone at full scale (perhaps a toolshed, playhouse, or garage).

Selected References

Allen, Edward, and Rob Thallon. *Fundamentals of Residential Construction* (4th ed.). Hoboken, NJ, John Wiley & Sons, 2017.

This book expands upon the chapters on residential-scale construction in the book you are now reading, giving full details of every aspect, including plumbing, mechanical and electrical systems, and landscaping.

American Forest & Paper Association. *Details for Conventional Wood Frame Construction.* Washington, DC, 2001.

This 55-page publication is available as a free download from the American Wood Council, at www.awc.org. It provides an excellent introduction to wood light framing methods and their use in residential construction, and includes design and construction guidelines and extensive illustrated details.

APA–The Engineered Wood Association. *Performance Rated I-Joists.* Tacoma, WA, 2015.

This publication is available as a free download from the APA–The Engineered Wood Association, at www.apawood.org. It provides guidelines and illustrated details for wood light framing with engineered I-joists.

International Code Council. *International Residential Code for One- and Two-Family Dwellings.* Falls Church, VA, updated regularly.

This is the definitive legal guide for platform frame residential construction throughout most of the United States. It includes details of every aspect of construction in both wood light frame and light gauge steel.

Thallon, Rob. *Graphic Guide to Frame Construction* (4th ed.). Newtown, CT, Taunton Press, 2016.

Unsurpassed for clarity and usefulness, this is an encyclopedic collection of details for wood platform frame construction.

Websites

American Wood Council: www.awc.org

APA–The Engineered Wood Association: www.apawood.org

Canadian Wood Council: www.cwc.ca

Fine Homebuilding magazine: www.finehomebuilding.com

Journal of Light Construction magazine: www.jlconline.com

Think Wood: www.thinkwood.com

Wood Design & Building magazine: www.wooddesignandbuilding.com

6

Exterior Finishes for Wood Light Frame Construction

- **Protection from the Weather**
  - Roofing Underlayment
  - Wall Water-Resistive Barriers
- **Roofing**
  - Finishing the Eaves and Rakes
  - Roof Drainage
  - Roof Overhangs and Rain Protection
  - Ventilated Roofs
  - Unventilated Roofs
  - Roof Shingling
- **Windows and Doors**
  - Flashings
  - Installing Windows and Doors

Paints and Coatings

- **Siding**
  - Board Siding
  - Plywood Siding
  - Shingle Siding
  - Metal and Plastic Siding
  - Stucco
  - Masonry Veneer
  - Artificial Stone
  - Fiber-Cement Panel Siding
- **Corner Boards and Exterior Trim**
- **Sealing Exterior Joints**

Sustainability and Paints and Other Architectural Coatings

- **Exterior Painting, Finish Grading, and Landscaping**
- **Exterior Construction**

Architects Hartman–Cox clad this small church with an economical but attractive siding of plywood and vertical wood battens, all painted white. The roofs are of asphalt shingles and the windows are of wood. The rectangular windows are double-hung. *(Photo by Robert Lautman, courtesy of American Wood Council.)*

As the rough carpentry of a platform frame building nears completion, a logical sequence of exterior finishing operations begins. First, the eaves and rakes of the roof are finished, which permits the roof to be shingled so as to offer as much weather protection as possible to subsequent operations. When the roof has been completed, the windows and doors are installed. Then the wall water-resistive barrier and siding are applied. The building is now "tight to the weather," allowing interior finishing work to take place safely sheltered from sun, rain, snow, and wind. The outside of the building is ready for exterior painting or staining. Finish grading, landscaping, and paving work may commence as electricians, plumbers, sheet metal workers, drywallers, finish carpenters, and flooring installers swarm about the interior of the building.

Figure 6.1
With roofing, skylights, doors, and windows installed, the interior of the structure can begin to dry out in preparation for interior finish work. *(Photo by Joseph Iano.)*

Protection from the Weather

Roofing Underlayment

In the interest of protecting the building structure from weather as quickly as possible, *roofing underlayment* is installed soon after the roof framing is completed and sheathed. This underlayment may consist of one or two layers of *building felt*, made of matted cellulose fibers saturated with asphalt, or *synthetic roofing underlayment*, made from woven polypropylene, polyethylene, or other synthetic fibers. During this stage of construction, the roofing underlayment serves as a temporary barrier to rain, allowing the structure to begin drying out in preparation for interior work. Once the underlayment is covered by the finish roofing, it continues to serve as a permanent backup layer, reducing the chance that wind-driven rain or minor leakage can penetrate into the roof structure. Traditionally, building felt was designated as either 15-lb or 30-lb, referring to the weight of material used to cover 100 square feet (9.2 m^2) of roof area. Contemporary standards specify roofing felt as either No. 15 or No. 30. Though still frequently referred to as 15-lb or 30-lb, today's felts actually weigh less than these names suggest. In comparison to roofing felt, synthetic underlayments tend to be lighter, more tear-resistant, less sensitive to prolonged exposure to sunlight, and more costly.

Wall Water-Resistive Barriers

Later during construction, the sheathed walls of the structure are also covered with a protective layer. This *water-resistive barrier* (*WRB*), or *weather barrier*, must be applied before siding is installed. Whether it is applied before or after the installation of doors and windows is usually up to the builder. The traditional materials used are either the same No. 15 felt used for roofing underlayment or an asphalt-saturated paper, called *Grade D building paper*, with similar properties.

Alternatives to traditional building felts and papers offer greater durability and the potential for increased energy efficiency by reducing air leakage through the building walls and roofs. More airtight *housewraps*, made of synthetic fibers, are manufactured in sheets as wide as 10 feet (3 m) in order to minimize seams (Figure 6.2). To further reduce air leakage, the seams may be sealed with tape provided by the housewrap manufacturer. Or, fully adhered sheets or liquid-applied membranes that cure in place may be used to provide even greater resistance to air leakage through the exterior walls. Collectively, these types of wraps and membranes may be referred to as *air and water-resistive barriers* (*AWBs*), reflecting their combined functions. The role of air barriers is discussed further in Chapter 7.

Walls and roofs may also be sheathed with OSB panels with a water-resistant and air-impermeable

FIGURE 6.2
Building felt covers most of the roof and housewrap covers the walls of this house under construction in preparation for the application of roofing and siding. The bottom few feet of the roof sheathing remain exposed, awaiting the application of a waterproof ice barrier material as described later in this chapter. *(Photo by Rob Thallon.)*

resin-and-paper overlay applied to the outer face of the panels in the factory. Once these panels are fastened to the wall or roof framing, panel seams are sealed with self-adhering tape and no additional barrier material is required.

Like roofing underlayment, the wall water-resistive barrier provides temporary protection from rain and wind during construction and, once finish siding is installed, acts as a permanent secondary line of defense against water infiltration. Although it is important that this barrier resist penetration of liquid water, it must, in most exterior wall designs, nevertheless also allow water vapor (water in a gas state) to pass relatively easily. Especially during cold months, interior humidity that tends to diffuse outward through the wall assembly must not become trapped behind the water-resistive barrier; rather, it must be allowed to continue to pass freely through to the exterior. For a more complete discussion of the control of liquid water and water vapor through the building enclosure, see Chapter 16.

ROOFING

Finishing the Eaves and Rakes

Before a roof can be shingled, the *eaves* (horizontal roof edges) and *rakes* (sloping roof edges) must be completed. Several typical ways of doing this are shown in Figures 6.3, 6.4, and 6.5. When designing eave and rake details, several objectives

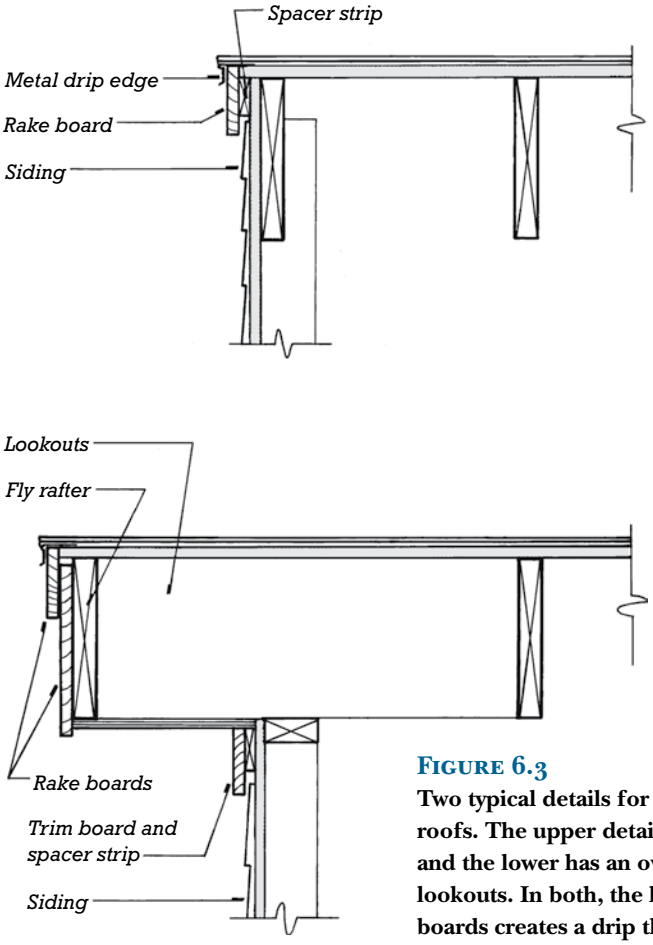


FIGURE 6.3
Two typical details for the rakes of sloping roofs. The upper detail has no rake overhang, and the lower has an overhang supported on lookouts. In both, the lower edge of the rake boards creates a drip that causes water to fall freely from the rake, rather than run down the siding below.

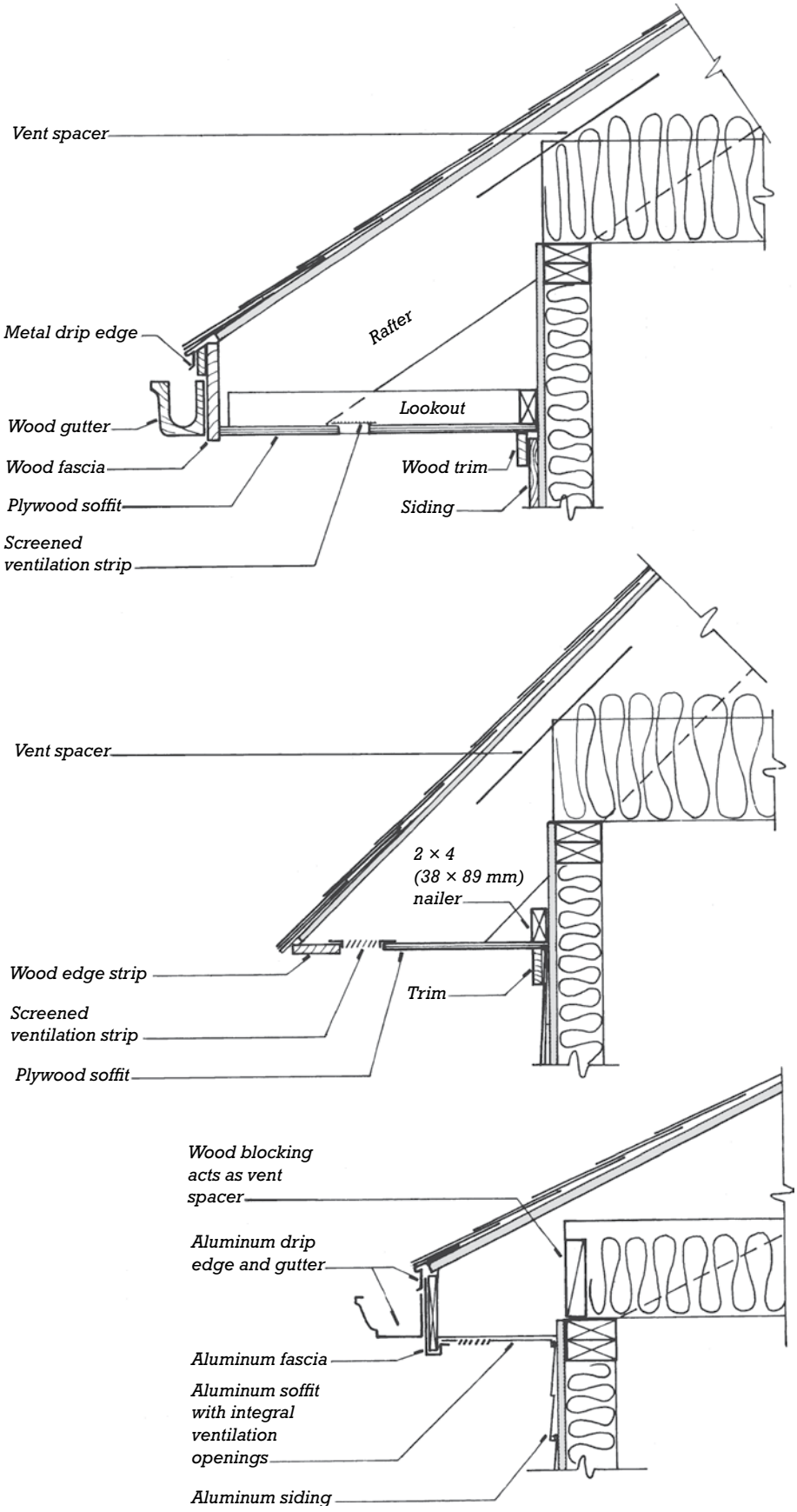


FIGURE 6.4
Three ways, from among many, of finishing the eaves of a light frame wood building. The top detail has a fascia and gutter, both of wood. The gutter is spaced slightly away from the fascia on blocks or shims to prevent moisture from being trapped between them, where it could lead to decay. The designer may vary the width of the overhang or may substitute a metal or plastic gutter for the wood one. The sloping line at the edge of the ceiling insulation indicates a vent spacer, as shown in Figure 6.7. The middle detail has no fascia or gutter; it works best for a steep roof with a sufficient overhang to drain water well away from the walls below. The bottom detail is finished entirely in aluminum. It shows wood blocking as an alternative to vent spacers for maintaining free ventilation through the attic.

should be kept in mind: The edges of the roof shingles should be positioned and supported in such a way that water flowing over them will drip free of the trim and siding below. Provision must be made to drain rainwater and snowmelt from the roof without damaging the structure below. In some roof assemblies, the eaves must be ventilated to allow free circulation of air beneath the roof sheathing. And siding, which is not installed until later, must fit easily against or into the eave and rake trim.

Roof Drainage

Gutters and *downspouts* (downspouts are also called *rain leaders*) are installed on the eaves of a sloping roof to remove rainwater and snowmelt without wetting the walls or causing splashing or erosion on the ground below. *External gutters* may be made of wood, plastic, aluminum, or other sheet metal and are fastened to the outer edge of the roof eave

FIGURE 6.5
An example of a badly done wood eave detail with an aluminum gutter and downspout. The carpentry at the intersection of the eave and the rake shows some poorly fitted joints and badly finished ends, and the soffit is not ventilated at all, which may lead to the formation of ice dams on the roof (see Figure 6.6) unless constructed as an unventilated roof, as explained in the text. *(Photo by Edward Allen.)*

(Figures 6.4 and 6.5). *Internal* (or *concealed*) *gutters*, which are recessed into the surface of the roof, are less common. They are difficult to waterproof, and if they do leak, they can cause more damage to the building structure and its finishes than can a leaky external gutter. Gutters are sloped toward the points at which downspouts drain away the collected water. On larger buildings, gutters and downspouts are sized using rainfall intensity data for the location in which the building is located and flow capacity formulas found in building and plumbing codes. At the bottom of each downspout, the water must be conducted away from the building to prevent soil erosion or basement flooding. A simple precast concrete *splash block* can spread the water and direct it away from the foundation, or a system of underground piping can collect the water from the downspouts and conduct it to a storm sewer, a *dry well* (an underground seepage pit filled with coarse crushed stone), or a drainage ditch.

Where collection of rainwater from roofs is not required by the building code or other regulations, gutters may be omitted and their associated problems of clogging and ice buildup avoided. Such roofs should be designed with eaves of sufficient depth to protect the wall below from excessive wetting by water falling from the roof edge. To prevent soil erosion and mud spatter from the falling water, the drip line at ground level below should be provided with a bed of crushed stone or other suitable surface material.

Roof Overhangs and Rain Protection

Roof eaves and overhangs play an important role in protecting buildings from the weather. Where ample overhangs are provided, the volume of rain that reaches the building wall is greatly reduced in comparison to walls without such protection, and the chance for water penetration into the walls is much less. The design of walls without overhangs should be approached with caution: These walls are more vulnerable to the effects of weather exposure, such as staining, leaking, decay, and premature deterioration of the windows, doors, and siding.

Ventilated Roofs

In cold climates, snow on a sloping roof tends to be melted by heat escaping through the roof from the heated space below. At the eave overhang, however, the shingles and gutter, which are not above heated space, can be much colder, and the snowmelt can refreeze and begin to build up layers of ice. If left unchecked, eventually an *ice dam* can form. Meltwater accumulating above the ice dam can then seep between the shingles, through the roof sheathing, and into the building, causing damage to walls and ceilings. Ice dams can be largely prevented by minimizing the temperature difference between roof areas over heated space and overhangs not over heated space. With a *ventilated roof*, this is accomplished by continuously passing outside air under the roof sheathing through vents at the eave and ridge. In buildings with an attic, the attic itself is ventilated. Insulation is installed in the ceilings below to retain the heat in the building. Where there is no attic and the insulation is installed between the rafters, the spaces between the rafters are ventilated by means of a continuous airspace between the insulation and the roof sheathing (Figures 6.6 and 6.7).

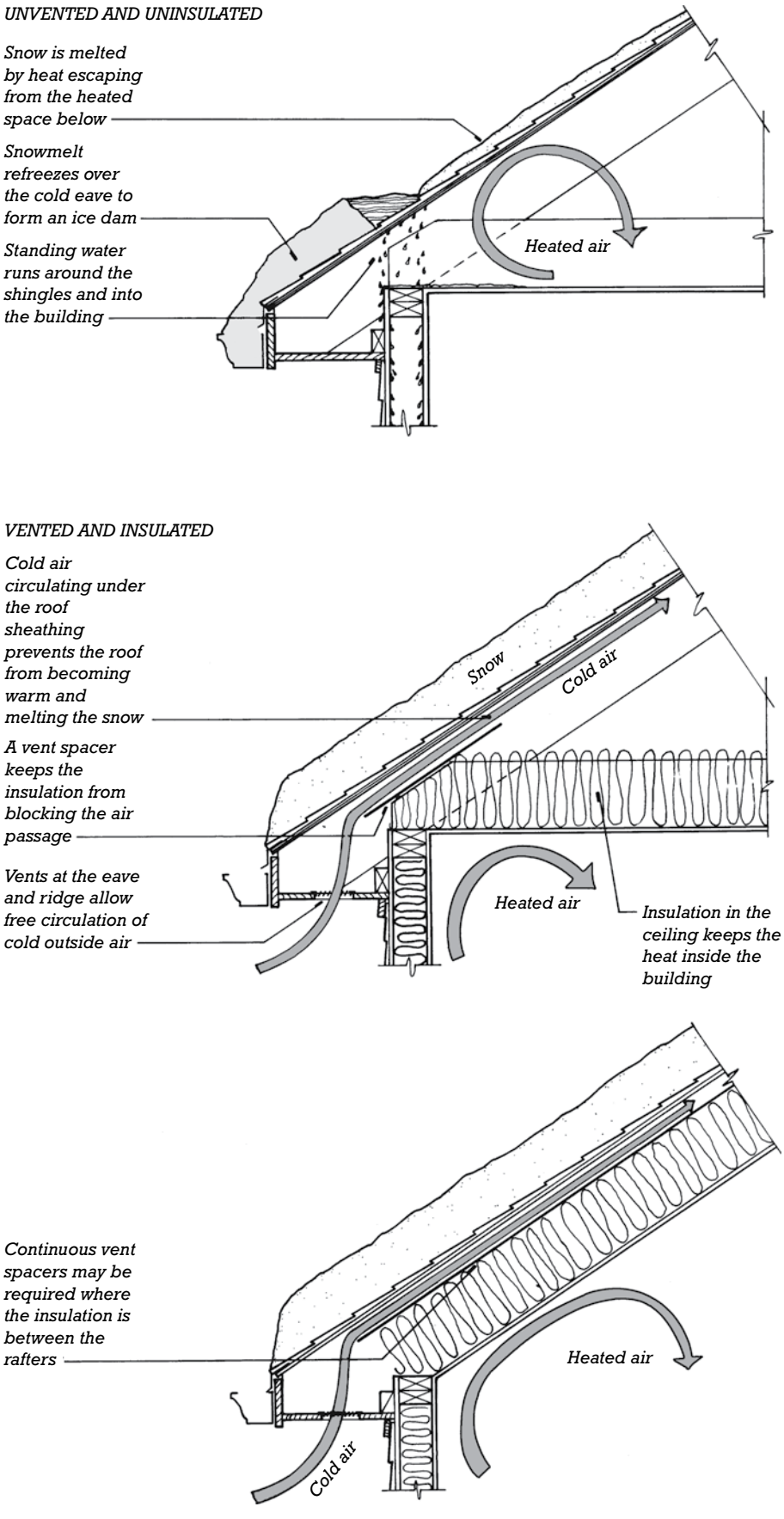


FIGURE 6.6
Ice dams form because of inadequate insulation combined with a lack of ventilation, as shown in the top diagram. The lower two diagrams show how insulation, attic ventilation, and vent spacers are used to minimize the melting of snow on the roof.

FIGURE 6.7
To maintain clear ventilation passages where thermal insulation materials come between the rafters, vent spacers of plastic foam or wood fiber are installed as shown here. The positioning of the blocking or vent spacers is shown in Figures 6.4 and 6.6. *(Proper Vent™ is a registered trademark of Poly-Foam Inc.)*

Soffit vents create the required ventilation openings at the eave; these usually take the form of a continuous slot covered with screening or a perforated aluminum strip made especially for the purpose (Figure 6.8). As an alternative to soffit vents, panels with hollow ventilation channels can be installed under the lowest several courses of roof shingles. A continuous slot running across the roof sheathing allows exterior air to circulate under the shingles, through the panel, and into the ventilation space under the roof sheathing. Ventilation openings at the ridge can be either *gable vents* just below the roof line in each of the end walls of the attic, or a continuous *ridge vent*, a screened cap that covers the ridge of the roof and draws air through gaps in the roof sheathing on either side of the ridge board (Figure 6.9). Building codes establish minimum area requirements for roof ventilation openings based on the floor area beneath the roof being ventilated.

In regions prone to ice damming, building codes also require an *ice barrier* to be installed along roof eaves. This may be several layers of roofing felt cemented together with asphalt, or more commonly, a self-adhered sheet of polymer-modified bitumen, referred to as *rubberized underlayment*, or as *ice and water* shield—the proprietary trade name of one of this type's products that has fallen into colloquial usage. The sheet must extend from the lowest edge of the roof to a line that is 2 feet (600 mm) inside the insulated space of the building (Figure 6.10). The soft, sticky bitumen seals around the shingle nails that are driven through it and prevents passage of water that may accumulate behind an ice dam. Alternatively, the lower portion of the sloped roof may be covered with sheet metal or other roofing material that is sufficiently waterproof to protect the roof from damage if ice damming occurs.

Rubberized underlayment may also be applied to other vulnerable portions of the roof surface, such as valleys or crickets behind chimneys. On lower-sloped roofs or in extreme exposures, rubberized underlayment may be applied over the entire roof sheathing, completely replacing other underlayments.

Roof ventilation serves other important purposes as well. It keeps a roof cooler in summer by dissipating solar heat absorbed by the shingles. A lower roof temperature extends the life of the roofing materials and reduces the heat load on the building interior. Roof ventilation also dissipates moisture that collects under the roof sheathing that may originate from leaks in the roofing or, in colder months, from warm, humid interior air that comes in contact with the cold underside of the roof sheathing.

In warmer climate zones, a variation on roof ventilation called *vapor diffusion ports* may be used. Soffit vents are eliminated, and ridge vents are replaced with similar openings sealed with an airtight but highly vapor permeable sheet material. Vapor diffusion ports prevent condensation under the roof sheathing by relieving the buildup of high humidity, which occurs first in the highest parts of the roof under the ridge. Unlike ventilated roofs, this configuration eliminates the risk of rain being driven into the roof assembly under high-wind conditions or from burning

FIGURE 6.8
A continuous soffit vent made of perforated sheet aluminum permits generous airflow to all the rafter spaces but keeps out insects. The walls of this building are covered with cedar shingles. *(Photo by Edward Allen.)*

FIGURE 6.9
This building has both a louvered gable vent and a continuous ridge vent to discharge air that enters through the soffit vents. The gable vent is of wood and has an insect screen on the inside. The aluminum ridge vent is internally baffled to prevent snow or rain from entering even if blown by the wind. The roofing is a two-layered asphalt shingle designed to mimic the rough texture of a wood shake roof. *(Photo by Edward Allen.)*

embers being drawn into the roof assembly during wildfire events.

Unventilated Roofs

Unventilated roofs can be constructed with insulated foam panels applied over the roof sheathing or with spray foam or rigid foam insulation boards applied below the sheathing between the roof rafters (Figure 6.11). When unventilated roofs are used in cold climates, protection from ice damming depends on ice barriers and the installation of sufficient insulation to reduce heat flow through the roof assembly, thereby slowing the melting of snow on the roof. Condensation resistance in unventilated roofs depends on the inability of significant quantities of air or water vapor to pass through the air-impermeable foam insulation to reach the colder layers of the roof assembly.

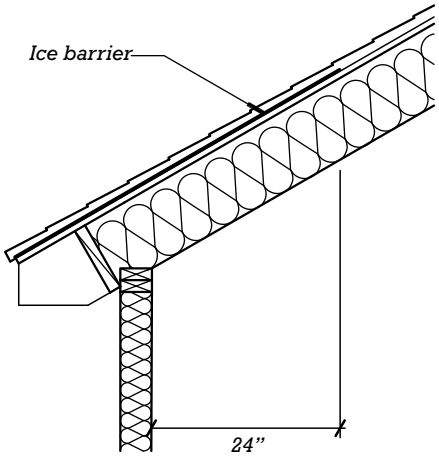


FIGURE 6.10
In cold climates, building codes require that an ice barrier be installed beneath the lowest courses of shingles. This must extend at least 24 inches (600 mm) over the insulated portion of the inhabited space.

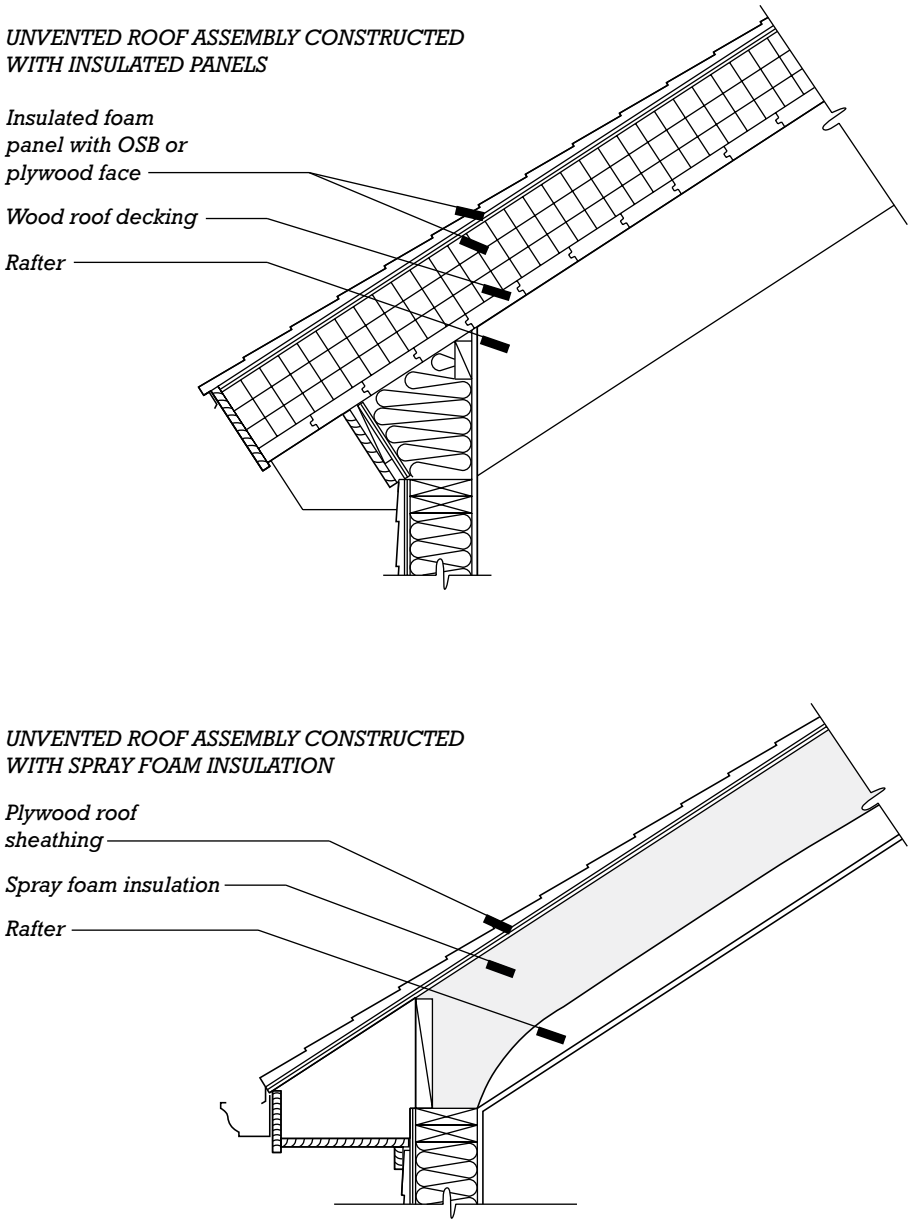


FIGURE 6.11
Two ways to build an unventilated roof assembly. In the top diagram, insulated foam panels are installed on top of wood decking. The insulated panels have a plywood or OSB face that provides a surface to hold the nails or staples for attaching the roof underlayment and shingles. The panels themselves are secured with screws long enough to penetrate through the panel into the roof decking or rafters below. In the lower diagram, foam insulation is sprayed against the underside of the roof sheathing. Depending on climate conditions, the thickness of foam insulation required to control condensation may vary from as little as 1 inch to as much as 7 inches (25 to 178 mm). Other types of insulation may be added beneath the foam where necessary to achieve the total required insulation value of the roof.

With insulated panels, special care must be taken to seal the panel joints where air leakage is most likely to occur. With spray foam insulation applied under the sheathing, the foam must have low permeability to airflow and, in cold climates, low water-vapor permeance as well. With rigid foam boards applied under the sheathing, edges of the boards must be carefully sealed to prevent the leakage of air around the boards. Where high roof temperatures are a concern (due to the lack of ventilation below the roof sheathing), shingles or other roof coverings with high solar reflectance may be considered, or insulated panels with integral ventilation channels may be used to create a ventilated assembly.

Advantages of unventilated roofing systems include simplicity of detailing, a thinner roof profile, less air leakage between the building interior and exterior, no risk of windblown water entry into the roof assembly through poorly baffled ridge vents, and no chance for burning embers to enter the roof assembly during a wildfire. However, the absence of ventilation also leaves this roof type potentially less able to dry out if moisture does find its way into the assembly. Where the potential for condensation is high (for example, in very cold climates or in roofs over high-humidity spaces), such assemblies should be analyzed and detailed to ensure that moisture conditions are adequately controlled.

Roof Shingling

Wood light frame buildings can be roofed with any of the materials described in Chapter 17. The least expensive, and most common, are *asphalt shingles*. These are applied either by the carpenters who have built the frame or by a roofing subcontractor (Figures 6.1 and 6.12). Wood shingle and shake roofs, clay and concrete tile roofs, and architectural sheet metal roofs are also common. Low-slope roofing membranes, either multi-ply bituminous or single-ply, may also be applied to a light frame building.

Windows and Doors

Flashings

Prior to the installation of windows and doors, *flashings* are installed to prevent water from seeping through gaps around the edges of these components. Flashings may be made of corrosion-resistant metals, plastics, synthetic fabrics similar to housewraps, modified bitumen sheets similar to the rubberized underlayment used for ice barriers on roofs, or liquid-applied compounds. The choice of materials varies with the type of door or window frame, the severity of the exposure to wind and rain, and the detailing of the surrounding trim. The most important flashing in a wall opening is the *sill flashing*, or *sill pan*. Any moisture that penetrates around the edges of the door or window frame tends to fall downward to the bottom of the wall opening. The sill flashing captures this water and ensures that it drains back to the exterior, preventing it from seeping further into the interior of the wall (Figures 6.13, 6.14, and 6.15).

Figure 6.12
Applying asphalt shingles over roofing felt. Shingles and other roof coverings are covered in detail in Chapter 16.
(Photo by Edward Allen.)

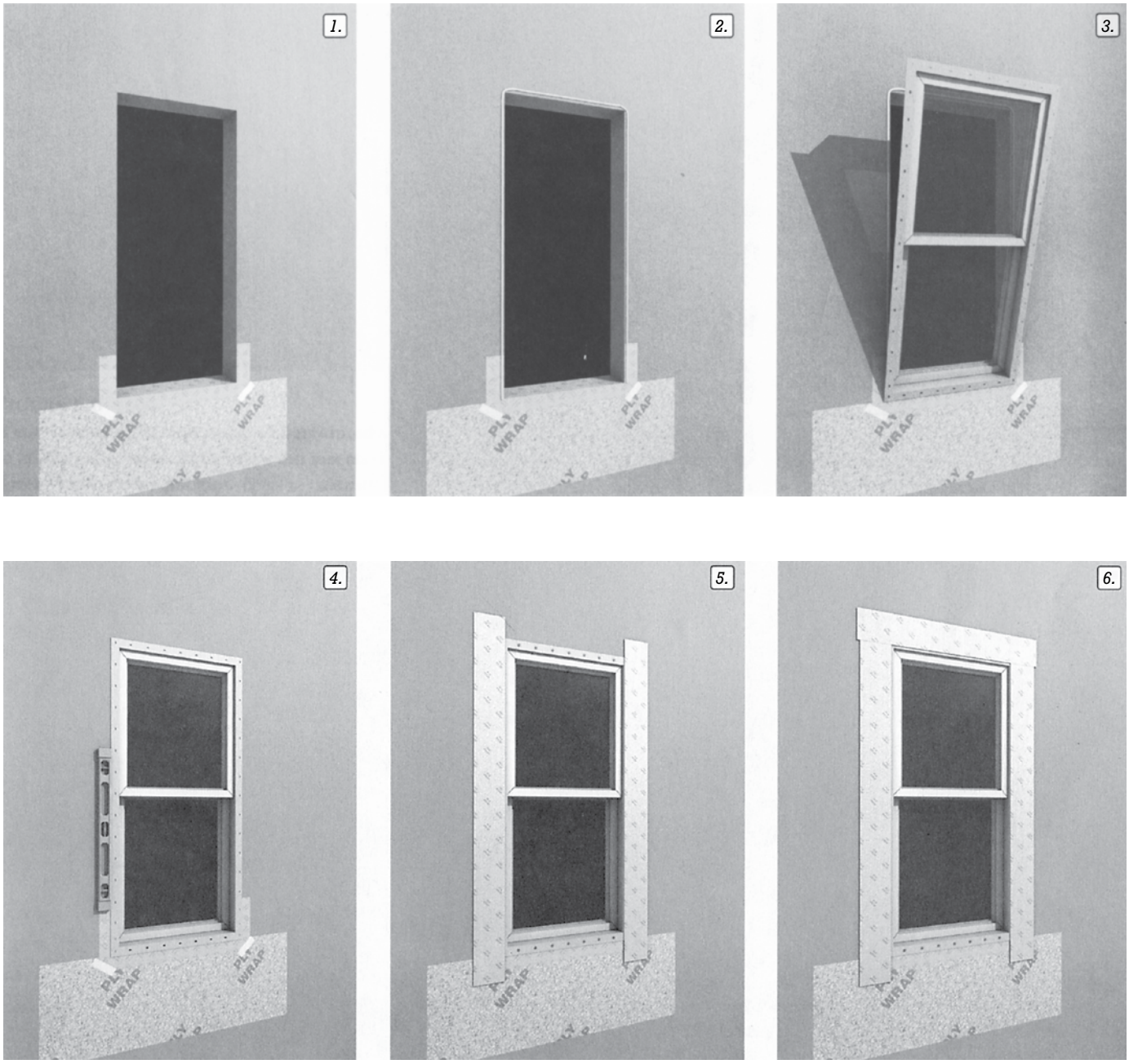


FIGURE 6.13

Steps in installing a vinyl-clad wood window in a wall covered with housewrap: *1.* With a single strip of self-adhering, flexible, waterproof sheet material, a U-shaped flashing is formed along the sill and up onto the side jambs. *2.* A bead of sealant is placed around the opening. *3.* The window unit is pushed into the opening from the outside. Its exterior flange is bedded in the sealant. *4.* One corner of the window unit is anchored with a nail through its flange and into the framing of the wall. With the aid of a level, a measuring tape, and thin wooden wedges, the unit is carefully squared as further nails are driven through the flanges. *5*, *6.* Strips of self-adhering waterproof sheet are adhered to the window flanges and housewrap over the side jambs and head for airtightness and watertightness.

FIGURE 6.14
Window flashing in a wall exposed to heavy, wind-driven rain. The metal sill pan is made of soldered copper. Underneath the copper is a self-adhered bituminous flashing. Beneath that, and surrounding the entire opening, is a synthetic fabric flashing. Behind the fabric flashing is the wall water-resistive barrier paper. The window opening itself is temporarily protected with plastic that will be removed before the window is installed. *(Photo by Joseph Iano.)*

FIGURE 6.15
Synthetic fabric flashing and a window unit installed in a wall opening. Housewrap has not yet been installed over the exterior sheathing. Sill flashing is missing from the installation. *(Photo by Edward Allen.)*

Installing Windows and Doors

Windows and doors are covered in detail in Chapter 19. *Nail-fin* (or *flanged*) *windows* are simple to install because they include a continuous flange around the perimeter through which nails are driven into the sheathing and studs (perpendicular to the wall plane) to fasten the units securely in place. The flange also provides a convenient surface for the application of self-adhering flashings. Most plastic-clad, aluminum, and solid plastic windows are manufactured as nail-fin types, as are some wood windows. *Finless* (or *flangeless*) *windows* and most doors do not have nailing flanges. They are fastened through the sides of the window or door frame into the supporting studs (parallel to the wall plane) with long finish nails or screws. The fasteners are either covered by additional trim or they are countersunk, with the resulting holes later filled with putty and painted over.

Residential entrance doors almost always swing inward and are mounted on the interior side of the door frame. This makes them less vulnerable to thieves who would remove hinge pins or use a thin blade to push back the latch to gain entrance. In cold climates, it also prevents snow that may accumulate against the door from preventing the door from opening. For improved wintertime thermal performance of the entrance, a storm door may be mounted on the outside of the same frame, swinging outward. The storm door usually includes at least one large panel of tempered glass. In summer, a screen door may be substituted for the storm door. Or a combination door, which has easily interchangeable screen and storm panels, can perform the role of both. A typical entrance door and details for its installation are shown in Figures 6.16 and 6.17.

Everybody loves window seats, bay windows, and big windows with low sills and comfortable chairs drawn up to them. . . . A room where you feel truly comfortable will always contain some kind of window place.

—Christopher Alexander et al., *A Pattern Language*, 1977

FIGURE 6.16
A six-panel wood entrance door with flanking sidelights and a fanlight above. A number of elaborate traditional entrance designs such as this are available from stock for use in light frame buildings. *(Courtesy of Morgan Products, Ltd.)*

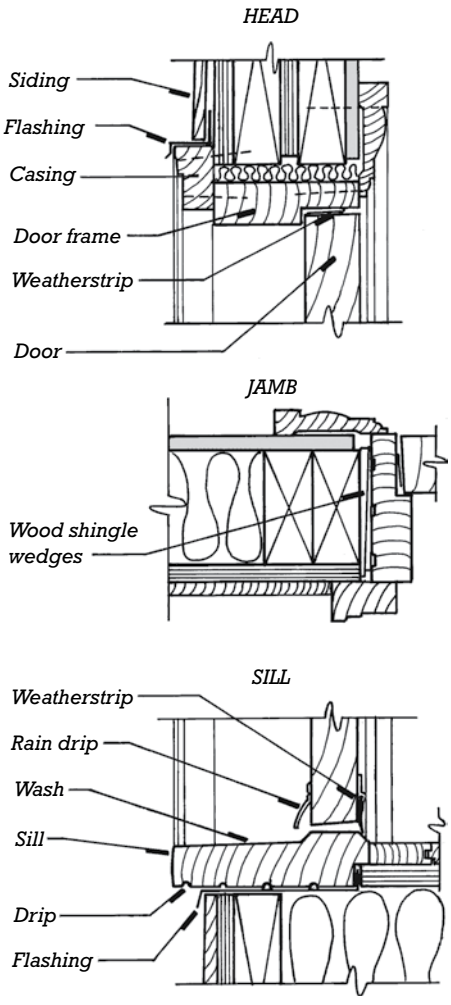


FIGURE 6.17
Details of an exterior wood door installation. The door opens toward the interior. The flashing in the head intercepts water running down the wall and directs it away from the door and frame. The sill flashing prevents water that penetrates around the door frame from leaking into the floor structure.

Paints and Coatings

Paints and other architectural coatings (stains, varnishes, lacquers, sealers) protect and beautify the surfaces of buildings. A good coating job begins with thorough surface preparation to make the surface (called the *substrate*) ready to receive the coating. The coating materials must be carefully chosen and skillfully applied using the proper tools and techniques. To finish the job, environmental conditions must be right for the drying or curing of the coating.

Material Ingredients

Most architectural coating materials are formulated with four basic types of ingredients: vehicles, solvents, pigments, and additives.

1. The *vehicle*, or *binder*, provides adhesion to the substrate and forms a film over it; it is often referred to as a *film-former*.
2. *Solvents* are volatile liquids used to improve the working properties of the paint or coating. The most common solvents used in coating materials are water and hydrocarbons, but turpentine, alcohols, ketones, esters, and ethers are also used.
3. *Pigments* are finely divided solids that add color, opacity, and gloss control to the coating material. They also impart hardness, abrasion resistance, and weatherability to the coating.
4. Additives modify various properties of the coating material. Driers, for example, are additives that hasten the curing of the coating. Other additives may relate to ease of application, resistance to fading, and other functions.

Solvent-Based Coatings and Water-Based Coatings

Coatings fall into two major groups: *solvent based* and *water based*. The most common solvents in solvent-based coatings are alkyd or polyurethane resins, or natural oils. These coatings cure by evaporation of the solvent, oxidation of the vehicle, or moisture curing from reaction of the vehicle with humidity in the air. Cleanup after painting is usually done with mineral spirits. Water-based coatings use water as the solvent. Most vehicles in water-based coatings are vinyl or acrylic resins. Cleanup is done with soap and water. In everyday use, solvent-based paints are most often referred to as "oil paints" or "alkyd paints" and the water-based paints as "latex paints."

Historically, water-based and solvent-based coatings each had uses for which they were preferred. Alkyd paints gave a smoother, harder surface than water-based paints and were favored for interior painting, especially where a durable, high-gloss finish was desired. Alkyd primers also offered superior covering ability and reliable adhesion to problematic substrates. In comparison, latex paints generated fewer odors during application than alkyd paints, an important consideration for renovation work where building occupants could be exposed to paint fumes. Where used for exterior finishing, latex paints produced a more flexible coating able to stretch without breaking when subjected to expansion and contraction of the substrate with changes in temperature and humidity. Latex coatings are also more breathable, lessening the chance of moisture being trapped behind painted siding or trim.

However, many solvent-based coatings also emit significantly more volatile organic compounds (VOCs) than water-based coatings. As pollution regulations and sustainability-influenced indoor air quality standards have placed increasingly strict limits on VOC emissions, the use of solvent-based coatings has decreased markedly. In response, manufacturers have improved the formulation of water-based coatings to the extent that, today, water-based coatings with low VOC or even no VOC emissions are available that can equal the performance of solvent-based coatings in almost all applications.

VOC emissions from solvent-based coatings can also be lowered by increasing the solids content and lowering the solvent content of the coating or using solvents that are exempt from low-VOC regulations. Also new to market are hybrid *alkyd-water emulsion coatings*, in which alkyd resins are suspended in water. These products offer many of the advantages of traditional alkyds, such as ease of application, excellent coverage, and durability, but in low-VOC formulations that can be cleaned up with water.

Types of Paints and Coatings

The various types of architectural coatings can be defined by the relative proportions of vehicle, solvent, pigment, and additives in each.

Paints contain relatively high amounts of pigment. The highest pigment content is in flat paints, those that dry to a completely matte surface texture. Flat paints contain a relatively low proportion of film-forming vehicle.

Paints that produce glossier surfaces are referred to as *enamels*. A high-gloss enamel contains a very high proportion of vehicle and a relatively low proportion of pigment. The vehicle cures to form a hard, shiny film in which the pigment is fully submerged. A semigloss enamel has a somewhat lower proportion of vehicle, though still more than a flat paint.

Stains range from transparent stains to semitransparent and solid stains. Transparent stains are intended only to change the color of the substrate, usually wood and sometimes concrete. They contain little or no vehicle or pigment, a very high proportion of solvent, and a dye additive. Excess stain is wiped off with a rag a few minutes after application, leaving only the stain that has penetrated the substrate. Usually, a surface stained with a transparent stain is subsequently coated with a clear finish, such as varnish, to bring out the color and figure of the wood and produce a durable, easily cleaned surface.

Semitransparent stains have more pigment and vehicle than transparent ones. They are not wiped after application. They are intended for exterior application in two coats and do not require a clear topcoat. Also self-sufficient are the solid stains, which are usually water-based. These contain much more pigment and vehicle than the other two types of stains and resemble a dilute paint more than they do a true stain. They are intended for exterior use.

The *clear coatings* are high in vehicle and solvent content and contain little or no pigment. Their purpose is to protect the substrate, make it easier to keep clean, and bring out its inherent beauty, whether it be wood, metal, stone, or brick. *Lacquers* are clear coatings that dry extremely rapidly by solvent evaporation. They are based on nitrocellulose or acrylics and are employed chiefly in factories and shops for rapid finishing of cabinets and millwork. A slower-drying clear coating is known as a *varnish*. Varnishes may be either solvent- or water-based. Most of them harden either by oxidation of an oil vehicle or by moisture curing. Varnishes are useful for on-site finishing. Varnishes and lacquers are available in gloss, semigloss, and flat formulations.

Shellac is a clear coating for interior use that is made from secretions of a particular Asian insect that have been dissolved in alcohol. Shellac dries rapidly and gives a very fine finish, but it is highly susceptible to damage by water or alcohol.

There are many finishes, intended primarily for furniture and indoor woodwork, that are based on simple formulations of natural oils and waxes. A mixture of boiled linseed oil and turpentine, rubbed into wood in many successive coats, gives a soft, water-resistant finish that is attractive to sight, smell, and touch. Waxes such as beeswax and carnauba can be rubbed over sealed (and sometimes unsealed) surfaces of wood and masonry to give a pleasingly lustrous finish. Finishes based on waxes and oils usually require periodic reapplication during service to maintain the character of the surface.

There are countless specialized coatings formulated for particular purposes. Intumescent coatings add fire resistance to steel (see Chapter 11). Industrial *high-performance coatings*, such as epoxies and urethanes, provide greater resistance to physical wear, chemical attack, and corrosion than are possible with ordinary paints. Asphaltic coatings may be applied to some roofing materials. Coatings based on portland cement may be applied over masonry or concrete.

Many of the newest and most durable architectural coatings are designed to be applied in the factory, where controlled environmental conditions and customized machines permit the use of many types of materials and techniques that would be difficult or impossible to use in the field. These include powder coatings, which are sprayed on dry and fused into continuous films by the application of heat; highly durable, multicomponent coating formulations, such as fluoropolymer finishes (see Chapter 21), and many others.

Field Application of Architectural Coatings

No aspect of painting and finishing work is more important than surface preparation. Unless the substrate is clean, dry, smooth, and sound, no paint or clear coating will perform satisfactorily. Normal preparation of wood surfaces involves scraping and sanding to remove any previous coatings, patching and filling holes and cracks, and sanding the surface to make it smooth. Preparation of metals may involve cleaning with solvents to remove oil and grease; scraping and wire brushing to remove corrosion and mill scale; sandblasting if the corrosion and scale are tenacious; and, on some metals, chemical etching of the bare metal to improve the paint bond. New masonry, concrete, and plaster surfaces generally require some aging before coating to ensure that the chemical curing reactions within the materials themselves are complete and that excess water has evaporated from the material.

A number of materials are designed specifically to prepare a surface to receive paints or clear coatings. Paste fillers are used to fill the small pores in open-grained woods such as oak, walnut, and mahogany prior to finishing. Various patching and caulking compounds serve to fill larger holes in substrates. A *primer* is a pigmented coating especially formulated to make a surface more paintable. A wood primer, for example, improves the adhesion of paint to wood. It also hardens the surface fibers of the wood so that it can be sanded smooth after priming. Other primers are designed as first coats for various metals, masonry materials, plaster, and gypsum

Paints and Coatings *(continued)*

board. Wood trim and casings in high-quality work are back primed by applying primer to their back surfaces before they are installed; this helps equalize the rate of moisture change on both sides of the wood during periods of changing humidity, which reduces cupping and other distortions. A *sealer* is a thin, unpigmented liquid that can be thought of as a primer for a clear coating. It seals the pores in the substrate so that the clear coating will not be absorbed.

To prevent premature drying, surfaces to be painted should not be exposed to direct sunlight, extreme temperatures, or high-speed winds. The paint materials themselves should also be at normal room temperature.

Paint and other coatings may be applied by brush, roller, pad, or spray. Brushing is the slowest and most expensive method; it is best for detailed work and for applying many types of stains and varnishes. Spraying is the fastest and least expensive, but also the most difficult to control. Roller application is economical and effective for large expanses of flat surface. Many painters prefer to apply transparent stains to smooth surfaces by rubbing with a rag that has been saturated with stain.

A single coat of paint or varnish is usually insufficient to cover the substrate and build the required thickness of film over it. A typical requirement for a satisfactory paint coating is one coat of primer plus two coats of finish material. Two coats of varnish are generally required over raw wood. The surface is lightly sanded after the first coat has dried to produce a smooth surface to which the final coat is applied.

Different coatings require curing periods that range from minutes for lacquers to days for some paints. During this time, environmental conditions similar to those required for the application of the coating must be maintained to ensure that the coating cures properly.

Deterioration of Paints and Finishes

Coatings are the parts of a building that are exposed to the most wear and weathering, and they deteriorate with time, requiring recoating. The ultraviolet (UV) component of sunlight is particularly damaging, causing fading of paint colors and chemical decomposition of paint films. Clear coatings are especially susceptible to UV damage, often lasting no more than a year before discoloring and peeling, which is why they are generally avoided in exterior locations. Some clear coatings are manufactured with special UV-blocking ingredients so that they may be used on exterior surfaces. The other major force of destruction for paints and other coatings is water. Most peeling of paint is caused by water getting behind the paint film and lifting it off. The most common sources of this water in wood sidings are lumber that is damp at the time it is coated, rainwater leakage at joints, and water vapor migrating from damp interior spaces to the outdoors during the winter. Good construction practices and proper design of air barriers and vapor retarders can minimize these problems.

Other major forces that cause deterioration of architectural coatings are oxygen, air pollutants, fungi, dirt, degradation of the substrate through rust or decay, and mechanical wear. Most exterior paints are designed to "chalk" slowly in response to these forces, allowing the rain to wash the surface clean at frequent intervals.

Typical Architectural Coating Systems

Figure A summarizes some typical specifications of coating systems for new surfaces of buildings. Especially where alkyd coatings are indicated, conformance of product VOC emissions to applicable limits should be verified.

Standards for Architectural Coating Systems

The Master Painters Institute (MPI) sets standards for paints and painting methods. Its manual of coating systems standardizes and simplifies the specification of complete coating systems, that is, combinations of surface preparation, primer, and topcoats appropriate for any given substrate and meeting a variety of performance levels.

Sustainability standards for paints and other architectural coatings continue to evolve. Green Seal's GS-11 Standard for Paints and Coatings sets performance standards for hiding power (opacity) and cleanability, limits VOC emissions, and restricts the inclusion of certain toxic or harmful ingredients in paints. Compliance with GS-11 is, at the time of this writing, recognized by LEED for credit for low-emitting architectural paints and coatings. MPI's Green Performance Standards establish criteria in the same categories of performance, emissions, and restricted ingredients, but in a manner that more closely coordinates with that organization's other product standards. Emissions limits set by the California Air Resources board are referenced in many sustainability guidelines, including the LEED rating system.

Substrate	Surface Preparation	Primer and Topcoats
Exterior		
Wood siding, trim, window, doors	Sand smooth, spot-prime knots and pitch streaks. Fill and sand surface blemishes after applying the prime coat.	Exterior latex (or alkyd primer where required by difficult substrate conditions) primer and two coats of latex paint; or two coats of semitransparent or solid stain
Concrete masonry	Must be clean and dry, at least 30 days old.	Block filler primer and two coats of latex paint
Concrete walls	Must be clean and dry, at least 30 days old.	Alkali-resistant masonry primer where required and two coats of latex paint
Stucco	Must be clean and at least 7 days old.	Alkali-resistant masonry primer where required and two coats of latex paint
Iron and steel	Remove rust, mill scale, oil, and grease.	General-purpose latex or corrosion-resistant metal primer and two coats of latex or alkyd enamel; or two coats of direct-to-metal latex enamel
Aluminum	Clean with a solvent to remove oil, grease, and oxide.	Latex metal primer and two coats of latex or alkyd enamel; or two coats of direct-to-metal latex enamel
Interior		
Plaster	Conventional plaster must be 30 days old (veneer plaster may be coated with latex paint immediately after hardening).	Latex primer sealer and two coats of latex paint
Gypsum board	Must be clean, dry, and free from dust.	Latex primer sealer and one or two coats of latex paint
Wood doors, windows, and trim	Sand smooth. Fill and sand small surface blemishes after applying the prime coat. Sand lightly between coats. Remove sanding dust before coating.	Interior latex or alkyd enamel primer and one or two coats of latex or alkyd enamel
Concrete masonry	Must be clean and dry, at least 30 days old.	Block filler primer and two coats of latex paint
Hardwood floors	Fill surface blemishes and sand before coating. Sand lightly between coats.	Oil stain if color change is desired, and two coats of oil or polyurethane varnish

FIGURE A

Siding

Exterior cladding materials applied to the walls of a wood light frame building are called *siding*. Many different types of materials may be used: wood boards with various profiles, applied either horizontally or vertically; plywood; wood shingles; metal or plastic materials; fiber-cement panels; brick or stone; and stucco.

Board Siding

Horizontally applied *board siding*, made of solid wood, wood composition board, or fiber-cement, is usually nailed through the wall sheathing, into the studs, ensuring secure attachment. *Siding nails*, whose heads are intermediate in size between those of common nails and finish nails, are used to give the best compromise between holding power and clean appearance when attaching horizontal siding. Siding nails should be hot-dip galvanized, or made of aluminum or stainless steel, to prevent corrosion and staining. Ringshank nails are preferred because of their better resistance to pulling out as the siding boards shrink and swell with changes in moisture content. Nailing is done in such a way that the individual pieces of siding may expand and contract freely without damage (Figure 6.18). Horizontal sidings are butted tightly to corner boards and window and door trim, usually with a sealant material applied to the joint during assembly.

More economical horizontal siding boards made of various types of wood composition materials are also available. Some of these have experienced problems in service with excessive absorption of water, decomposition, or fungus growth, while others have established a successful track record. Board sidings made from wood fiber in a portland

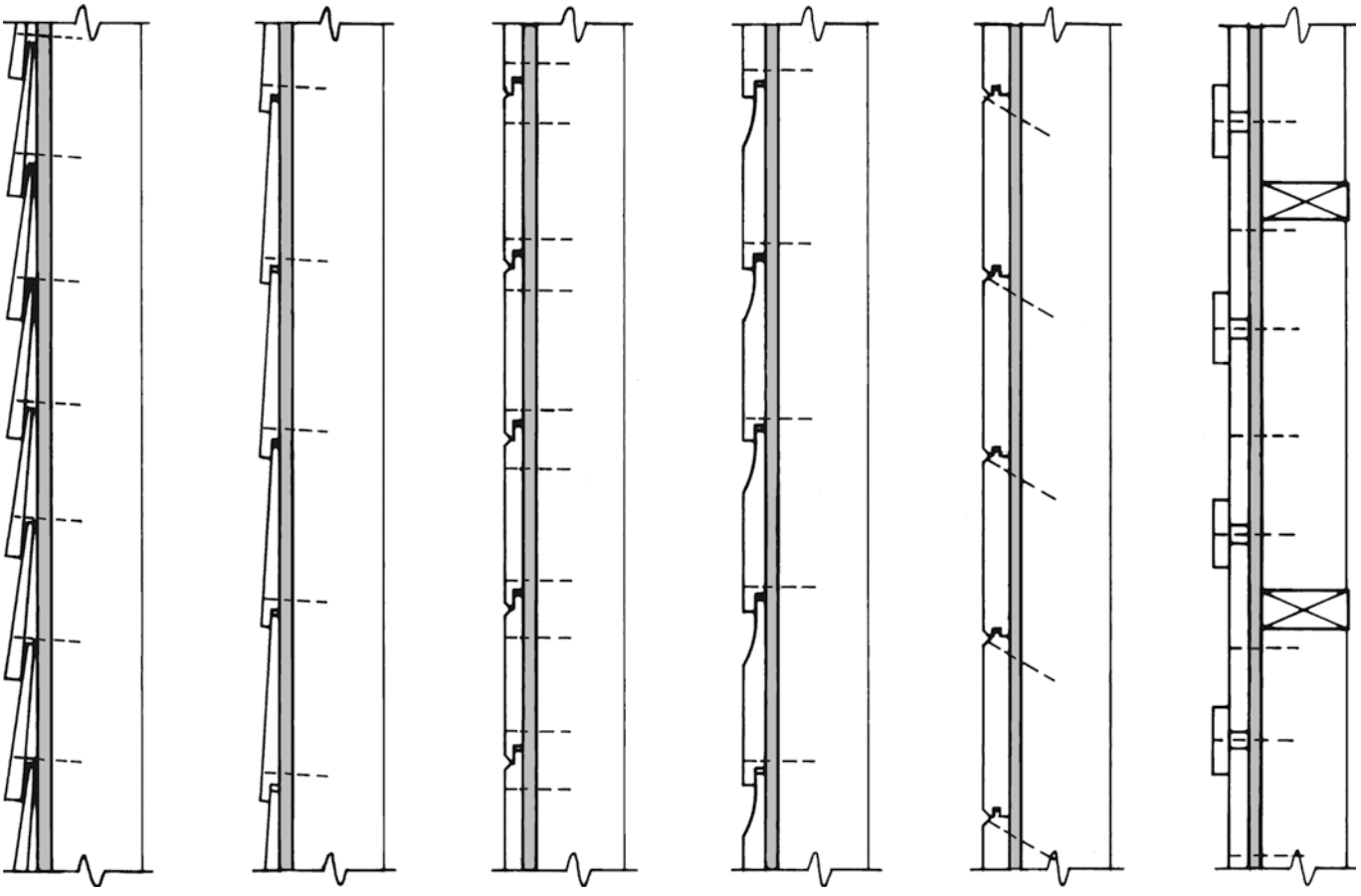


Figure 6.18

Six types of wood siding from among many. The four *bevel* and *shiplap* sidings are designed to be applied in a horizontal orientation. *Tongue-and-groove* siding may be used either vertically or horizontally. *Board-and-batten* siding may only be applied vertically. The nailing pattern (shown with broken lines) for each type of siding is designed to allow for expansion and contraction of the boards. Nail penetration into the sheathing and framing should be a minimum of 1½ inches (38 mm) for a satisfactory attachment.

cement binder have also proven to perform well in service. They accept and hold paint well, do not decay or support fungus growth, and are dimensionally stable, resistant to fire, and very durable.

Siding boards are frequently nailed tight to the wall water-resistive barrier and sheathing. Alternatively, horizontal siding may be nailed over vertical wood spacers called *furring strips*, usually made from preservative-treated 1 × 3s (19 × 63 mm) or similar preservative-treated plywood or plastic that are aligned over the studs (Figure 6.19). Such *drained cladding*, or *rainscreen cladding*, allows water that seeps through the siding to readily drain out of the assembly rather than soak further into the wall, permits more rapid drying of the siding should it become soaked, and enhances the wall's capability to dispel water vapor that could otherwise accumulate within the wall. With furred siding, special attention must be given to corner boards and window and door casings to account for the overall thickness of the cladding. Alternatively, thin drainage mat materials or dimpled or crinkled water-resistive barrier membranes, which can be sandwiched between

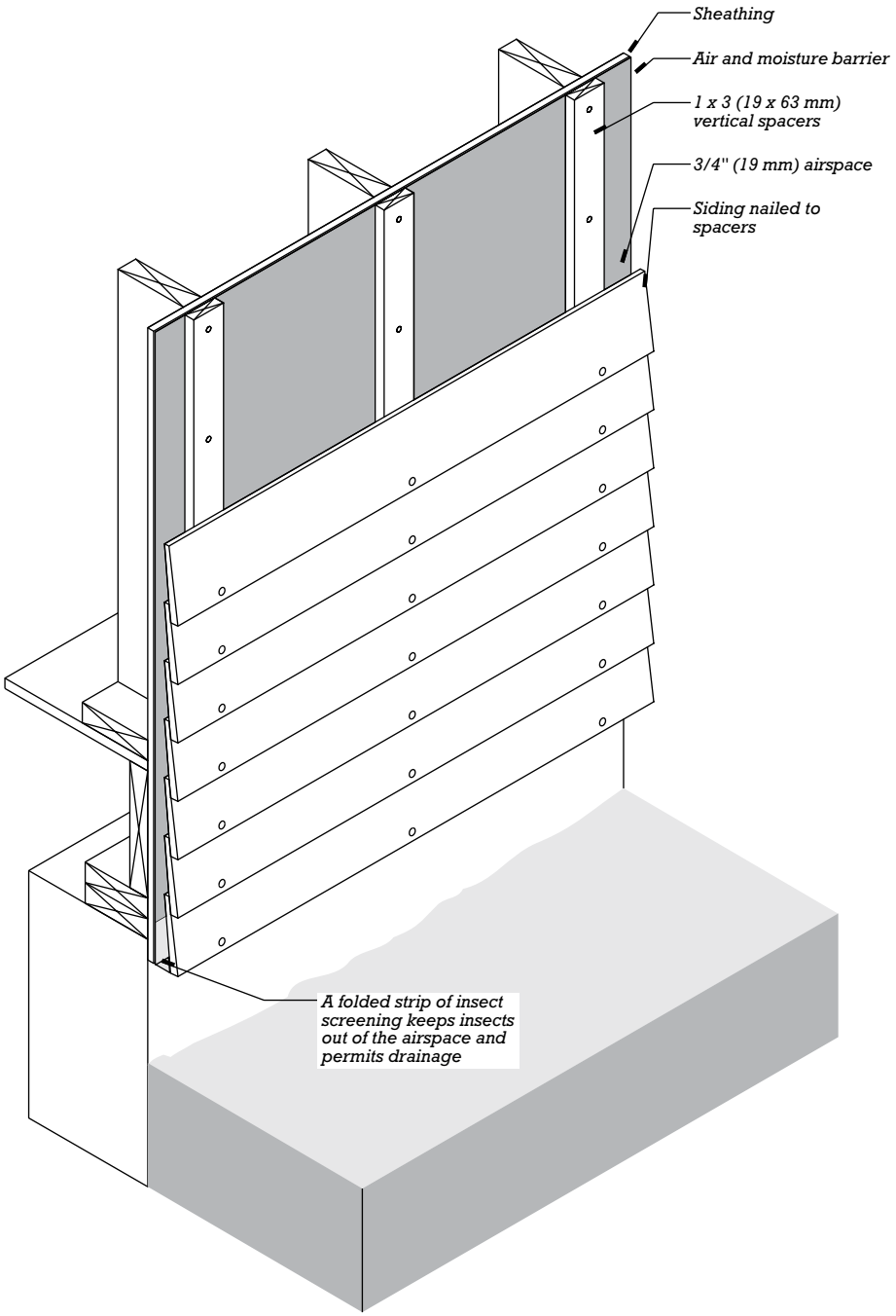


FIGURE 6.19
Drained cladding. Water that penetrates through gaps in the siding drains away before it reaches the sheathing. With vertical siding, horizontal wood furring strips are not practical, as they would block the drainage space. Instead, plastic furring strips with crosswise hollow channels may be used. The open channels in the furring allow water to pass through.

the siding and the water-resistive barrier, can be used to provide some improvement in drainage and ventilation in comparison to conventional siding installations, but at lower cost and with less impact on the detailing of exterior trim in comparison to siding over vertical furring.

When a rainscreen cladding drainage space is sufficiently deep to promote air movement behind the cladding (approximately ⅜ inch, 10 mm, or more), the cladding may be called *ventilated cladding*, if the drainage space is open at both the top and bottom, or *vented cladding*, if the drainage space is open at the bottom only. Ventilated cladding provides superior air movement and greater drying potential behind the cladding in comparison to vented cladding.

Vertically applied sidings (Figures 6.20 and 6.21) are nailed at the top and bottom plates of the wall framing and at one or more intermediate horizontal lines of wood blocking installed between the studs.

Heartwood redwood, cypress, and cedar sidings may be left unfinished if desired to weather to various shades of gray. The bare wood will erode gradually over a period of decades and will eventually have to be replaced. Other woods must be either

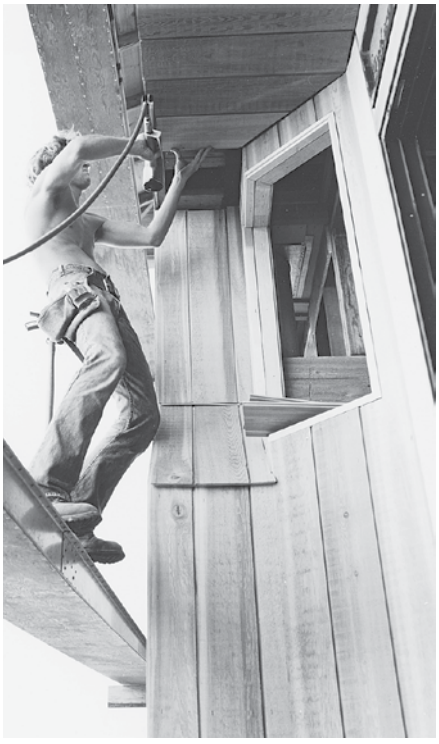


Figure 6.20
A carpenter applies V-groove tongue-and-groove redwood siding to an eave soffit, using a pneumatic nail gun. *(Courtesy of Senco Products, Inc.)*

Figure 6.21
A completed installation of tongue-and-groove siding, vertically applied in the foreground of the picture and diagonally in the area seen behind the chairs. The lighter-colored streaks are sapwood in this mixed heartwood/sapwood grade of redwood. The windows are framed in dark-colored aluminum. *(Architect: Zinkhan/Tobey. Photo by Barbeau Engh, courtesy of California Redwood Association.)*

stained or painted to prevent weathering and decay. If these coatings are renewed faithfully at frequent intervals, the siding beneath will last indefinitely.

Plywood Siding

Plywood panel siding (Figure 6.22) is often chosen for its economy. The cost of the material per unit area of wall is usually less than for other siding materials, and labor costs tend to be lower because the large sheets of plywood are more quickly installed than equivalent areas of boards. In some cases, sheathing can also be eliminated from the building (with the wall water-resistive barrier applied directly to the studs), yielding further cost savings. All plywood sidings must be painted or stained, even those made of decay-resistant heartwoods, because their veneers are too thin to withstand weather erosion for more than a few years. The most popular plywood sidings are those that are grooved to imitate board sidings and conceal the vertical joints between sheets.

The largest problem in using plywood sidings for multistory buildings is how to detail the horizontal panel joints between sheets. A *Z-flashing* of aluminum (Figure 6.23) is the usual solution, but remains clearly visible.

Figure 6.22
Grooved plywood siding is used vertically on this commercial building by Roger Scott Group, Architects. The horizontal metal flashings between sheets of plywood are purposely emphasized here with a special projecting flashing detail that casts a dark shadow line. *(Courtesy of APA–The Engineered Wood Association.)*

Shingle Siding

Wood shingles and heavier *shakes* (Figures 6.24 through 6.30) require a *nail-base sheathing* material such as OSB or plywood. Either corrosion-resistant box nails or gun-driven staples may be used for attachment. Most shingles are of cedar or redwood heartwood and do not need to be coated with paint or stain unless such a finish is desired for cosmetic reasons.

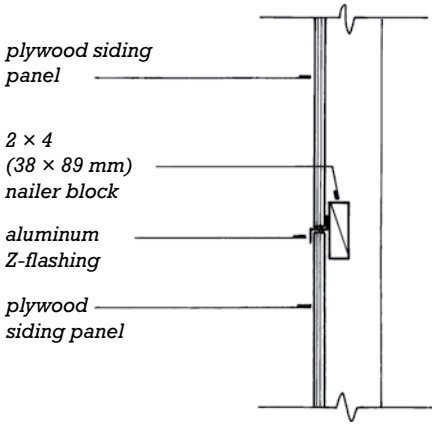


Figure 6.23
A detail of a simple Z-flashing, the device most commonly used to prevent water penetration at horizontal joints in plywood siding.

FIGURE 6.24
Applying wood shingle siding over asphalt-saturated felt building paper. The corners are woven as illustrated in Figure 6.26. *(Photo by Edward Allen.)*

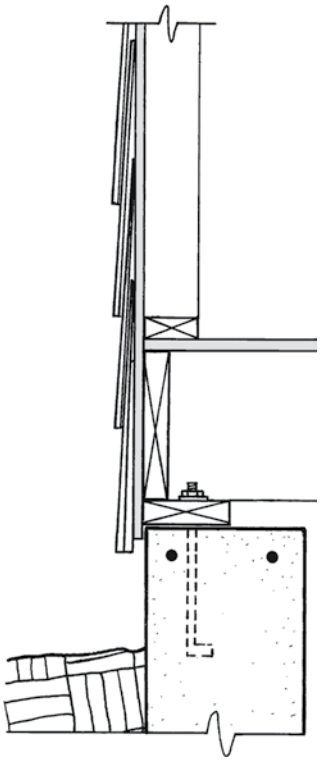


FIGURE 6.25
A detail of wood shingle siding at the sill of a wood platform frame building. The first course of shingles projects below the sheathing to form a drip, and is doubled so that all the open vertical joints between the shingles of the outside layer are backed up by the undercourse of shingles. Succeeding courses are single but are laid so that each course covers the open joints in the course below.

The application of wood shingle siding is labor-intensive, especially around corners and openings, where many shingles must be cut and fitted. Figures 6.26 and 6.27 show two different ways of turning corners with wood shingles. Several manufacturers produce shingle siding in panel form by stapling and/or gluing shingles to wood backing panels in a factory. A typical panel size is approximately 2 feet high and 8 feet long (600 × 2450 mm). Several different shingle application patterns are available in this form, along with prefabricated woven corner panels. Panelized shingles can be applied much more rapidly than individual shingles, which results in sharply lower on-site labor costs and, in most cases, a lower overall cost.

Metal and Plastic Siding

Painted wood sidings are apt to deteriorate unless they are carefully scraped and repainted every

Figure 6.26
Wood shingles can be woven at the corners to avoid corner boards. Each corner shingle must be carefully trimmed to the proper line with a block plane, which is time-consuming and relatively expensive, but the result is a more continuous, sculptural quality in the siding.

Figure 6.27
Corner boards save time when shingling walls and become a strong visual feature of the building. Notice in this figure and Figure 6.26 how the joints and nail heads in each course of shingles are covered by the course above.

three to six years. *Aluminum* and *vinyl sidings*, formed of prefinished sheets of aluminum or molded of vinyl plastic, respectively, are usually designed to imitate wood sidings and are generally guaranteed against needing repainting for many years (Figures 6.31 and 6.32). Such sidings do have their own problems, however, including the poor resistance of aluminum sidings to denting and the tendency of plastic sidings to crack and occasionally shatter on impact, especially in cold weather. Although plastic and aluminum sidings bear a superficial similarity to the wood sidings that they mimic, their details around openings and corners in the wall are sufficiently different that they are usually inappropriate for use in historic restoration projects.

Stucco

Stucco, or *portland cement plaster*, is a strong, durable, economical,

FIGURE 6.28
Fancy cut wood shingles were often a featured aspect of shingle siding in the late 19th century. Notice the fish-scale shingles in the gable end, the serrated shingles at the lower edges of walls, and the sloping double-shingle course along the rakes. Corners are woven. *(Photo by Edward Allen.)*

FIGURE 6.29
Fancy cut wood shingles stained in contrasting colors are used here on a contemporary restaurant. *(Courtesy of Red Cedar Shingle & Handsplit Shake Bureau.)*

FIGURE 6.30
Both the roof and walls of this New England house by architect James Volney Righter are covered with wood shingles. Wall corners are woven. *(© Nick Wheeler/Wheeler Photographics.)*

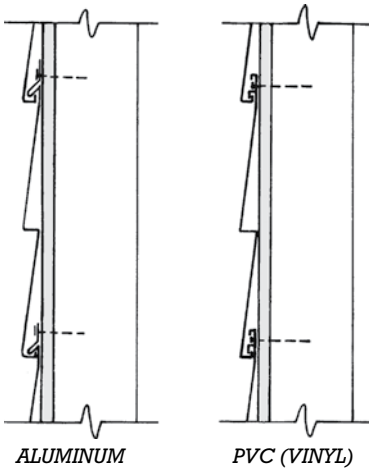


FIGURE 6.31
Aluminum and vinyl sidings are both intended to imitate wood horizontal bevel siding. Their chief advantage in either case is low maintenance. Nails are completely concealed in both systems.

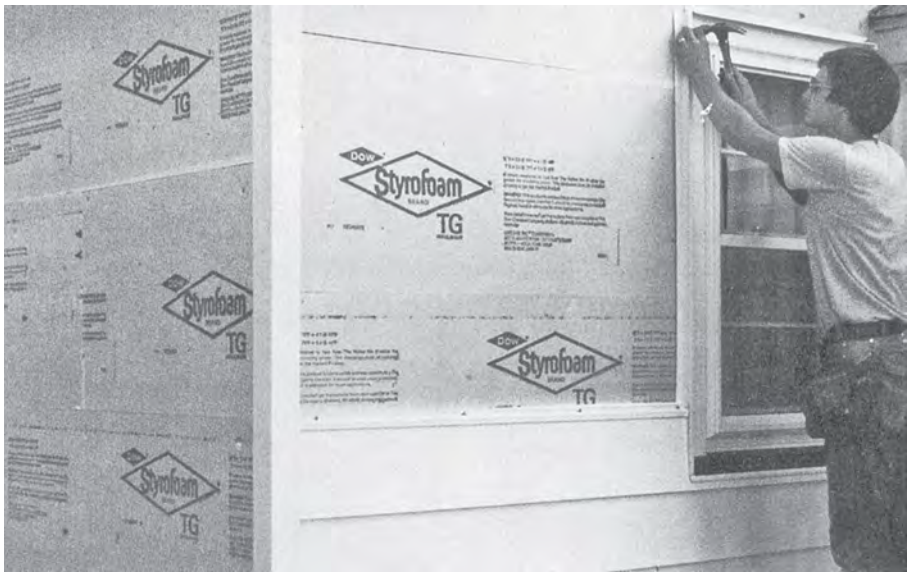


FIGURE 6.32
Retrofitting aluminum siding over insulating foam sheathing on an existing residence. Special aluminum pieces are provided for corner boards and window casings; each piece has a shallow edge channel to accept the cut ends of the siding. *(Photo provided by the Dow Chemical Company.)*

fire-resistant cladding material. It is normally applied in three coats over wire lath, either by hand or by spray apparatus (Figures 6.33 and 6.34). Despite its monolithic appearance, stucco is a porous material and prone to the development of hairline shrinkage cracks. When it is used in locations exposed to wind and rain, significant quantities of water can pass through the material. In such circumstances, stucco is best installed as a drained cladding with a drainage mat or drainage space between it and the water-resistive barrier.

Masonry Veneer

Light frame buildings can be faced with *masonry veneer*, a single wythe of brick or stone, in the manner shown in Figure 6.35. The corrugated metal ties prevent the masonry from falling away from the building while allowing for differential vertical movement

FIGURE 6.33
Applying exterior stucco over woven wire lath, often referred to as "chicken wire." The workers to the right hold a hose that sprays the stucco mixture onto the wall, while the man at the left levels the surface of the stucco with a straightedge. The small rectangular opening at the base of the wall is a crawlspace vent. *(Courtesy of Keystone Steel & Wire Co.)*

FIGURE 6.34
This small Los Angeles office building demonstrates the plasticity of form that is possible with stucco siding. Vertical and horizontal joints in the stucco minimize its tendency to shrink and crack as it dries out after curing. Although the building is supported from below on concrete columns and steel girders, it is actually a wood light frame building. *(Eric Owen Moss Architects. Photo © Tom Bonner '97.)*

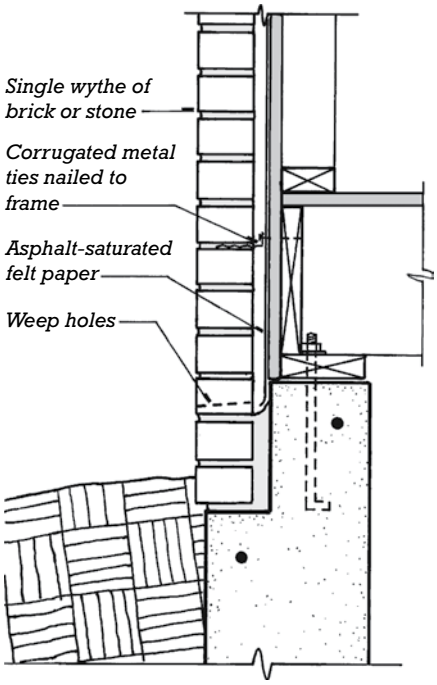


FIGURE 6.35
A detail of masonry veneer facing for a platform frame building. The weep holes drain any moisture that might collect in the cavity between the masonry and the sheathing. The cavity should be at least 1 inch (25 mm) wide. A 2-inch (50-mm) cavity is better because it is easier to keep free of mortar droppings that can clog the weep holes.

Figure 6.36
Well-crafted brick veneer, stucco, and painted exterior finish carpentry are combined in this early 20th century home. *(Photo by Joseph Iano.)*

between the masonry and the frame. Like stucco, brick veneer is a porous material. The cavity behind the brick creates a drained cladding system that helps to protect the wood-framed wall from water penetration. Masonry materials and detailing are covered in Chapters 8 and 9.

Artificial Stone

Artificial stone, or *manufactured masonry*, is made from mixtures of cement, sand, other natural aggregates, and mineral pigments such as iron oxide. It is cast into any of a great variety of shapes, textures, and colors simulating the appearance of traditional brick and natural stone products but applied as a thin facing. Artificial stone units range in thickness from approximately 1 inch to 2⅝ inches (25 to 67 mm) and are typically applied over a base of metal lath and portland cement plaster in a manner similar to that of stucco.

Fiber-Cement Panel Siding

Fiber-cement panel siding is made of cement, sand, organic or inorganic fibers, and fillers manufactured into panels usually 4 feet × 8 feet (1219 mm × 2438 mm) in size and ¼ or 5⁄16 inch (6 or 8 mm) thick. They are manufactured with a smooth face or with various textures, and can be painted in the field or provided prefinished. They are attached with nails or screws driven into the wall studs or other solid framing behind the wall sheathing. Gaps between panels can be sealed with joint sealant or filled with preformed plastic or aluminum trim.

Corner Boards and Exterior Trim

Most siding materials require vertical corner boards as well as trim boards around windows and doors. Roof edges require trim boards of various types, including fascias, soffits, frieze boards, and moldings, the exact patterns depending on the style and detailing of the building (Figure 6.37). For most sidings, the traditional choice of material for these exterior trim components is pine. For wood shingles, unpainted cedar or redwood may be preferred. Plastic and metal sidings are trimmed with special accessory strips of the same material. Fiber-cement siding may be trimmed either with wood or with fiber-cement boards made for the purpose.

A high-appearance grade of pine is usually chosen for wood trim boards. Traditionally, the boards are back primed before installation, with the application of a prime coat of paint on the back side. This helps to reduce cupping and other distortions of the trim boards with changes of humidity. Fully preprimed trim boards are also available at most lumberyards.

Many historical styles require trim that is ornamentally shaped. The shaping generally takes place at a mill so that the trim pieces come to the site ready to install.

As appearance grades of lumber have become more costly, substitutes have been introduced to the market, including boards made of high-density plastic foams, wood composites of various kinds, and lumber that has been cut into short pieces

Figure 6.37
Painters finish the exterior of a house. The painter at the far left is standing on the top of a stepladder—a very unsafe practice.
(Courtesy of Energy Studies in Buildings Laboratory, Center for Housing Innovation, Department of Architecture, University of Oregon.)

to eliminate knots, then reassembled end-to-end with finger joints and glue. These products tend to be more consistently straight and free of defects than natural, solid lumber. Some of them are not only produced as flat boards, but also molded to imitate traditional trim. They must be painted and are not suitable for transparent finishes. Many are also available preprimed or prefinished.

Sealing Exterior Joints

After the completion of exterior carpentry work, exposed gaps between siding, trim, frames of doors and windows, and other exterior materials are sealed with *joint sealant*, traditionally called *caulk*, to protect against the entry of water. Exterior sealants must have good adhesion to the materials being sealed, remain permanently flexible, and be unaffected by exposure to sunlight. *Paintable sealants* can be installed before finish painting and then painted over to match adjacent surfaces. Other sealants, such as many silicones, cannot hold paint. These are selected from a range of available premixed colors and then applied after finish painting. Sealant materials and sealant joint design are discussed in detail in Chapter 16.

Figure 6.38
Careful detailing is evident in every aspect of the exterior finishes of this commercial building. Notice especially the cleanly detailed window casings, the purposeful use of both vertical boards and wood shingles for siding, and the neat junction between the sidewall shingles and the rake boards. *(Woo & Williams, Architects. Photographer: Richard Bonarrigo.)*

Figure 6.39
This house in a rainy climate is designed to shelter every window and door with a roof overhang. The base of the wall is sided with water-resistant cement board. Special attention to roof overhang proportions, exposed framing details, window muntin patterns, and railing details gives this house a uniquely appealing character. *(Photo by Rob Thallon.)*

Sustainability and Paints and Other Architectural Coatings

Material and Production Attributes

- Unused paint can be reprocessed to make *recycled paint*, eliminating this material from the waste disposal stream.

Unhealthful Materials and Emissions

- Paints and other coatings can be significant emitters of *volatile organic compounds* (*VOCs*), chemical air pollutants, and potential health hazards to construction workers and building occupants.
- Water-based acrylic latex paints generally have lower VOC emissions than solvent-based paints. High-solids content coatings also have low VOC emissions.
- To protect indoor air quality, LEED, Living Building Challenge, and WELL Building Standard establish maximum VOC content requirements for interior paints and coatings. These programs also require testing of interior paints and coatings to verify that actual emissions from these materials do not exceed prescribed limits.
- In some cases, sustainability programs limit VOC content in exterior paints and coatings as well.
- Ecolabel programs, such as Green Seal, establish additional criteria for paints and coatings, such as limits on heavy metals, ozone-depleting contents, carcinogens, reproductive toxins, and more.
- Paints that wear quickly and require frequent recoating may increase VOC emissions over the life of a facility in comparison to others with higher emissions that are more durable and require less frequent recoating.

Exterior Painting, Finish Grading, and Landscaping

The final steps in finishing the exterior of a light frame building are painting or staining of exposed wood surfaces; finish grading of the ground around the building; installation of paving for drives, walkways, and terraces; and seeding and planting of landscape materials. By the time these operations take place, interior finishing operations are also usually well underway, having begun as soon as the roofing, sheathing, windows, and doors were in place.

Exterior Construction

Wood is widely used outdoors for porches, decks, stairs, stoops, and retaining walls (Figure 6.40). Decay-resistant heartwoods, wood that is pressure treated with preservatives, and moisture-resistant wood/plastic composite planks are

Figure 6.40
Exterior carpentry for this residential addition includes ipe decking and painted pine railings and trim. The decking is spaced to allow water to drain through. *(Photo by Michael Craig Moore, AIA.)*

MasterFormat Sections for Exterior Finishes for Light Wood Frame Construction

04 20 00	**UNIT MASONRY**
04 21 13.13	Brick Veneer Masonry
04 73 00	**MANUFACTURED STONE MASONRY**
06 20 00	**FINISH CARPENTRY**
06 20 23	Exterior Finish Carpentry
06 53 00	**PLASTIC DECKING**
06 65 00	**PLASTIC SIMULATED WOOD TRIM**
07 25 00	**WEATHER BARRIERS**
07 26 00	**AIR BARRIERS**
07 31 00	**SHINGLES AND SHAKES**
07 31 13	Asphalt Shingles
07 31 29	Wood Shingles and Shakes
07 32 00	**ROOF TILES**
07 46 00	**SIDING**
07 46 16	Aluminum Siding
07 46 23	Wood Siding
07 46 29	Plywood Siding
07 46 33	Plastic Siding
07 46 46	Fiber-Cement Siding
07 62 00	**SHEET METAL FLASHING AND TRIM**
07 65 00	**FLEXIBLE FLASHING**
07 65 26	Self-Adhering Sheet Flashing
08 14 00	**WOOD DOORS**
08 50 00	**WINDOWS**
09 24 00	**CEMENT PLASTERING**
09 91 00	**PAINTING**
09 93 00	**STAINING AND TRANSPARENT FINISHING**

suitable for these exposed uses. If nondurable woods are used, they will soon decay at the joints, where water is trapped and held by capillary action. Fasteners must be hot-dip galvanized, specially coated, or stainless steel to avoid corrosion. Wood decking that is exposed to the weather should always have open, spaced joints to allow for drainage of water through the deck and for expansion and contraction of the decking. Plastic composite planks are durable and attractive, although some are not as strong or stiff as wood, and may require more closely spaced joists for support.

Key Terms

roofing underlayment
building felt
synthetic roofing underlayment
water-resistive barrier (WRB), weather barrier
Grade D building paper
housewrap
air and water-resistive barrier (AWB)
eave
rake
gutter
downspout, rain leader
external gutter
internal gutter, concealed gutter
splash block
dry well
ice dam
ventilated roof
soffit vent
gable vent
ridge vent
ice barrier
rubberized underlayment, ice and water shield
vapor diffusion port
unventilated roof
asphalt shingle
flashing
sill flashing, sill pan
nail-fin window, flanged window
finless window, flangeless window
substrate (for painting)
vehicle, binder, film-former
solvent
pigment
solvent-based coating
water-based coating
alkyd-water emulsion coating
paint
enamel
stain
clear coating
lacquer
varnish
shellac
high-performance coating
primer
sealer
siding
board siding
siding nail
bevel siding
shiplap siding
tongue-and-groove siding
board-and-batten siding
furring strip
drained cladding, rainscreen cladding
ventilated cladding
vented cladding
plywood panel siding
Z-flashing
wood shingle
wood shake
nail-base sheathing
aluminum siding
vinyl siding
stucco, portland cement plaster
masonry veneer
artificial stone, manufactured masonry
fiber-cement panel siding
joint sealant
caulk
paintable sealant
recycled paint
volatile organic compound (VOC)

Review Questions

1. In what order are exterior finishing operations carried out on a platform frame building, and why?

2. At what point in exterior finishing operations can interior finishing operations begin?

3. What are the reasons for the relative economy of plywood sidings? What special precautions are advisable when designing a building with plywood siding?

4. How does one make corners when siding a building with wood shingles?

5. Specify two alternative exterior coating systems for a building clad in wood bevel siding.

6. What are the usual reasons for premature paint failure on a wood-sided house?

Exercises

1. For a completed wood frame building, make a complete list of the materials used for exterior finishes and sketch a set of details of the eaves, rakes, corners, and windows. Are there ways in which each could be improved?

2. Visit a building materials supply store and look at all the alternative choices of sidings, windows, doors, trim lumber, and roofing. Study one or more systems of gutters and downspouts. Look at eave vents, gable vents, and ridge vents.

3. For a wood light frame building of your design, list precisely and completely the materials you would like to use for the exterior finishes. Sketch a set of typical details to show how these finishes should be applied to achieve the appearance you desire, with special attention to the roof edge details.

Selected References

Hanley Wood Media. *Journal of Light Construction*. Washington, DC, published monthly.

A magazine that is an excellent reference on all aspects of wood light frame construction, including topics related to exterior carpentry and finishing (see also *Fine Homebuilding*).

National Roofing Contractors Association. *The NRCA Roofing Manual: Steep-Slope Roof Systems*. Rosemont, IL, updated regularly.

This industry-standard reference provides guidelines and recommended details for asphalt shingle roofing and other types of steep-slope roofing.

Taunton Press. *Fine Homebuilding*. Newtown, CT, published monthly.

A magazine that is an excellent reference on all aspects of wood light frame construction, including topics related to exterior carpentry and finishing (see also *Journal of Light Construction*).

Williams, R. Sam. "Finishing of Wood." In Forest Products Laboratory, *Wood Handbook: Wood as an Engineering Material*. Madison, WI, 1999.

This article provides a comprehensive introduction to the topic of wood finishing. It can be viewed online for free on the Forest Product Laboratory's website, www.fpl.fs.fed.us. The complete handbook is also available in printed form from various publishers.

Websites

Andersen Windows & Doors: www.andersenwindows.com

Benjamin Moore Paints: www.benjaminmoore.com

Building Science Corporation: www.buildingscience.com

Cabot Stains: www.cabotstain.com

Cedar Shake & Shingle Bureau: www.cedarbureau.org

Fleetwood Windows & Doors: www.fleetwoodusa.com

Green Seal: www.greenseal.org

James Hardie Fiber Cement Siding: www.jameshardie.com

Master Painters Institute (MPI): www.paintinfo.com

MPI Specify Green: www.specifygreen.com

National Roofing Contractors Association: www.nrca.net

Olympic Paints and Stains: www.olympic.com

Pella—Windows and Doors: www.pella.com

Portland Cement Association—Stucco (Portland Cement Plaster): www.cement.org/learn/materials-applications/stucco

Quantum Windows & Doors: www.quantumwindows.com

Sherwin-Williams Coatings: www.sherwin-williams.com

Vinyl Siding Institute: www.vinylsiding.org

Western Red Cedar Lumber Association: www.realcedar.com

7

Interior Finishes for Wood Light Frame Construction

- **Completing the Building Enclosure**
  - Insulating the Building Frame
  - Increasing Levels of Thermal Insulation
  - Radiant Barriers
  - Vapor Retarders

  Sustainability and Insulation Materials for Wood Light Frame Construction

  - Air Barriers
  - Infiltration and Ventilation
- **Wall and Ceiling Finish**
- **Millwork and Finish Carpentry**
  - Interior Doors

  Proportioning Fireplaces

  - Window Casings and Baseboards
  - Cabinets
  - Finish Stairs
  - Miscellaneous Finish Carpentry

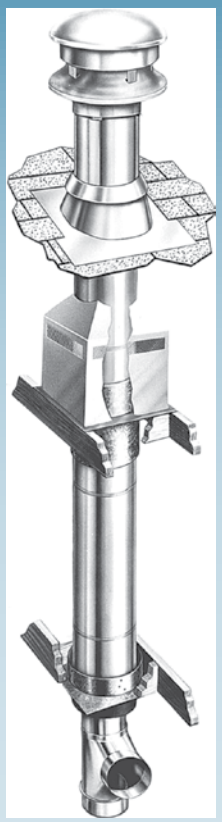
  Proportioning Stairs
- **Flooring and Ceramic Tile Work**
- **Finishing Touches**

Architect Michael Craig Moore uses a rich palette of stone and wood contrasting with light-colored walls and ceiling surfaces. In the foreground is slate flooring. Stairs and wood floors are heartwood-only pine ("heart pine"). Wood cabinets and trim are vertical grain Douglas fir. Cabinet counters and the windowseat top (middle ground of the image) are a composite sheet material made from compressed paper and phenolic resin. Cabinet pulls are bronze. The exposed structural wood column, to the right in the image, is also Douglas fir. Wood surfaces are finished with clear polyurethane. Walls and ceilings are covered with gypsum wallboard finished with latex primer and topcoats. *(Photo by Michael Craig Moore, AIA.)*

As the exterior roofing and siding of a platform frame building approach completion, the framing carpenters and roofers are joined by workers from additional building trades. Masons commence work on fireplaces and chimneys (Figures 7.1 and 7.2). Plumbers begin roughing in their piping (*roughing in* refers to the process of installing the components of a system that will not be visible in the finished building). First to be installed are the large *DWV (drain–waste–vent) pipes*, which drain by gravity and must therefore have first choice of space in the building; then the small *supply pipes*, which bring hot and cold water to the fixtures, and the gas piping (Figures 7.3 through 7.6). If the building will have central warm air heating and/or air conditioning, sheet metal workers install the furnace and *ductwork* (Figures 7.7, 7.8, and 7.9). If the building is to have a *hydronic (forced hot water) heating* system, the plumbers put in the boiler and rough in the heating pipes and *convectors* at this time (Figure 7.10). A special variety of hydronic heating is the *radiant heating* system, which warms the building floors by circulating hot water through plastic piping built into the floors (Figure 7.11). The electricians are usually the last of the mechanical and electrical trades to complete their roughing in because their wires are flexible and can generally be routed around other pipes and ducts without difficulty (Figure 7.12). When the various trades have completed their rough work, which consists of everything except installing the plumbing fixtures, electrical outlets, and air registers and grills, inspectors from the local building department check each of the systems for compliance with the plumbing, electrical, and mechanical codes, as well as to ensure that framing has not been damaged during the installation of these other components.

Once these inspections have been passed, connections are made to external sources of water, gas, electricity, and communications services, and to a means of sewage disposal (either a sewer main or a septic tank and leaching field). Thermal insulation and, if needed, a vapor retarder are added to the exterior ceilings and walls.

Now a new phase of construction, the interior finishing operations, begins, during which the



inside of the building undergoes a succession of dramatic transformations. The elaborate tangle of framing members, ducts, pipes, wires, and insulation rapidly disappears behind the finish wall and ceiling materials. The interior millwork—doors, finish stairs, railings, cabinets, shelves, closet interiors, and door and window casings—is installed. The finish flooring materials are installed as late in the process as possible to save them from damage by the passing armies of workers, and carpenters follow behind the flooring installers to add the baseboards that cover the last of the rough edges in the construction.

Finally, the building is visited by the painters who prime, paint, stain, varnish, and paper its interior surfaces. The plumbers, electricians, and sheet metal workers make brief return appearances on the heels of the painters to install the plumbing fixtures; the electrical receptacles, switches, and lighting fixtures; and the air grills and registers. At last, following a final round of inspections and a last-minute round of repairs and corrections to remedy lingering defects, the building is ready for occupancy.

FIGURE 7.1
(*Opposite page*) Insulated metal flue systems are often more economical than masonry chimneys for furnaces, boilers, water heaters, package fireplaces, and solid-fuel stoves. *(Courtesy of Selkirk Metalbestos.)*

Interactive Exercise

FIGURE 7.2
A mason adds a section of clay flue liner to a chimney. The large flue is for a fireplace, and the three smaller flues are for a furnace and two woodburning stoves. *(Photo by Edward Allen.)*

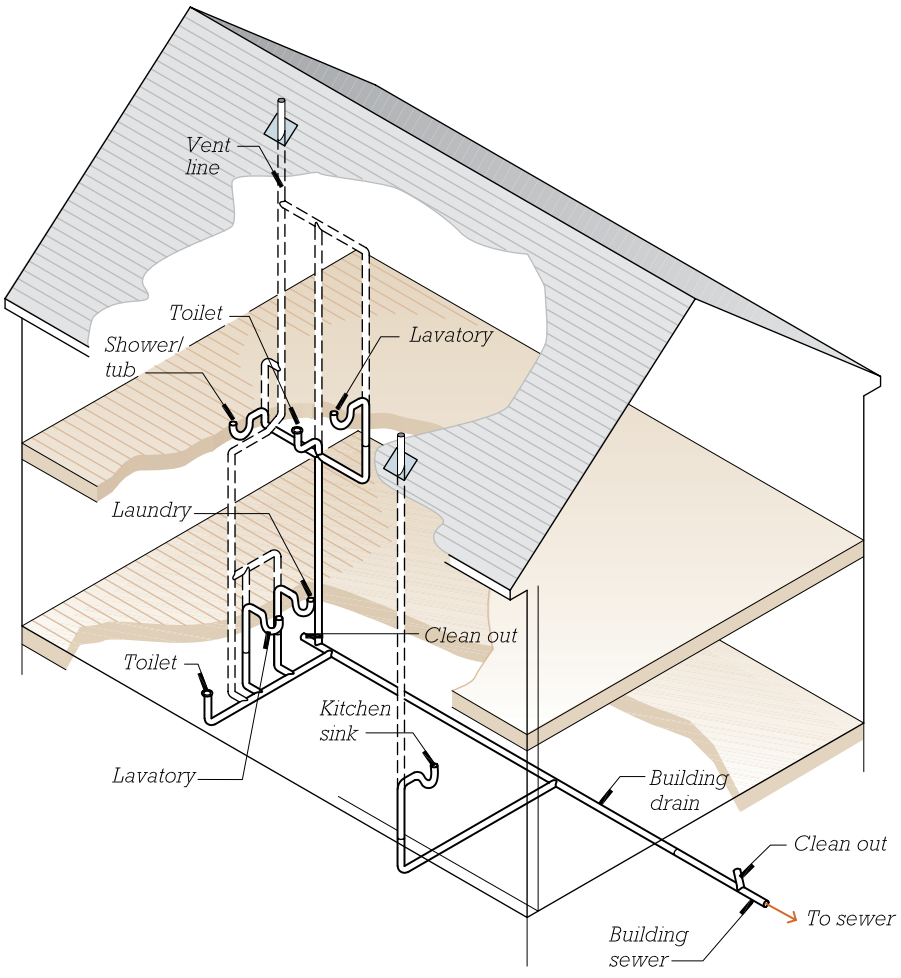
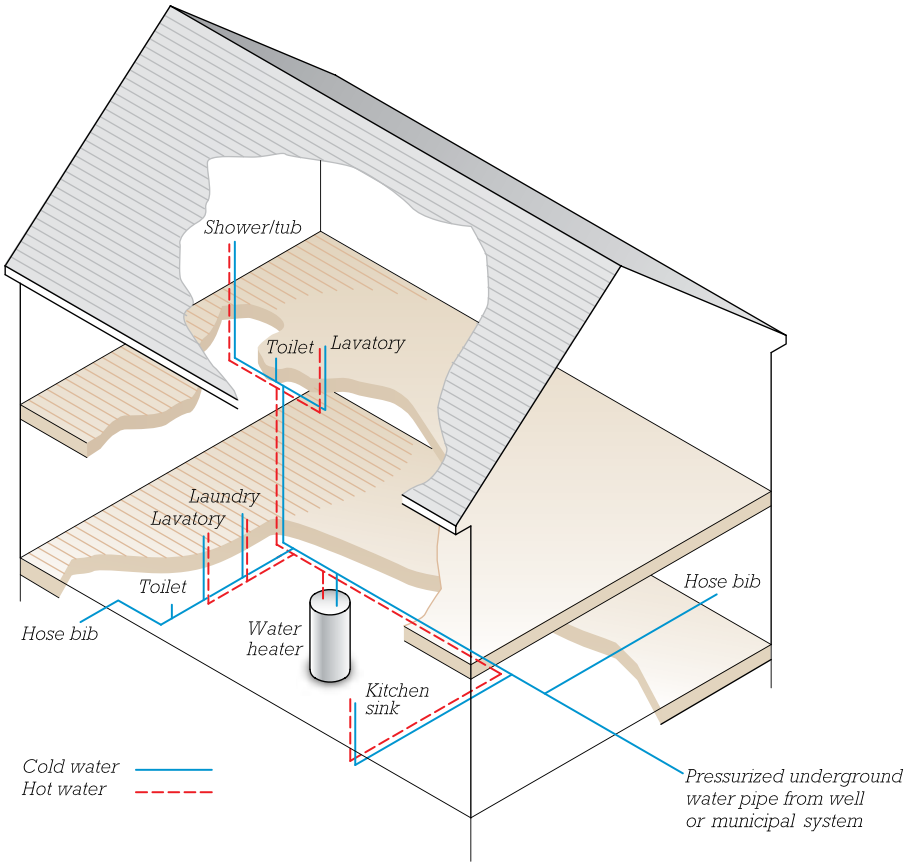


FIGURE 7.3
A typical residential wastewater system. All fixtures drain to the building drain through sloping or vertical branch lines. The waste pipe is vented to the exterior at each fixture through a network of vent pipes, shown with broken lines.

FIGURE 7.4
A typical residential water supply system. Water enters the house through a buried line and branches into two parallel sets of distribution lines. One is for cold water. The other passes through the water heater and supplies hot water. In a *trunk and branch distribution* system, as shown here, larger trunk lines carry hot and cold water to different areas of the building where smaller lines then branch out to individual fixtures. In a *home run distribution* system, smaller-diameter pipes running from a central distribution manifold supply each fixture throughout the home individually. Home run systems rely on flexible, *cross-linked polyethylene* (*PEX*) *plastic piping*, resulting in many fewer piping connections and quicker delivery of hot and cold water to each fixture.



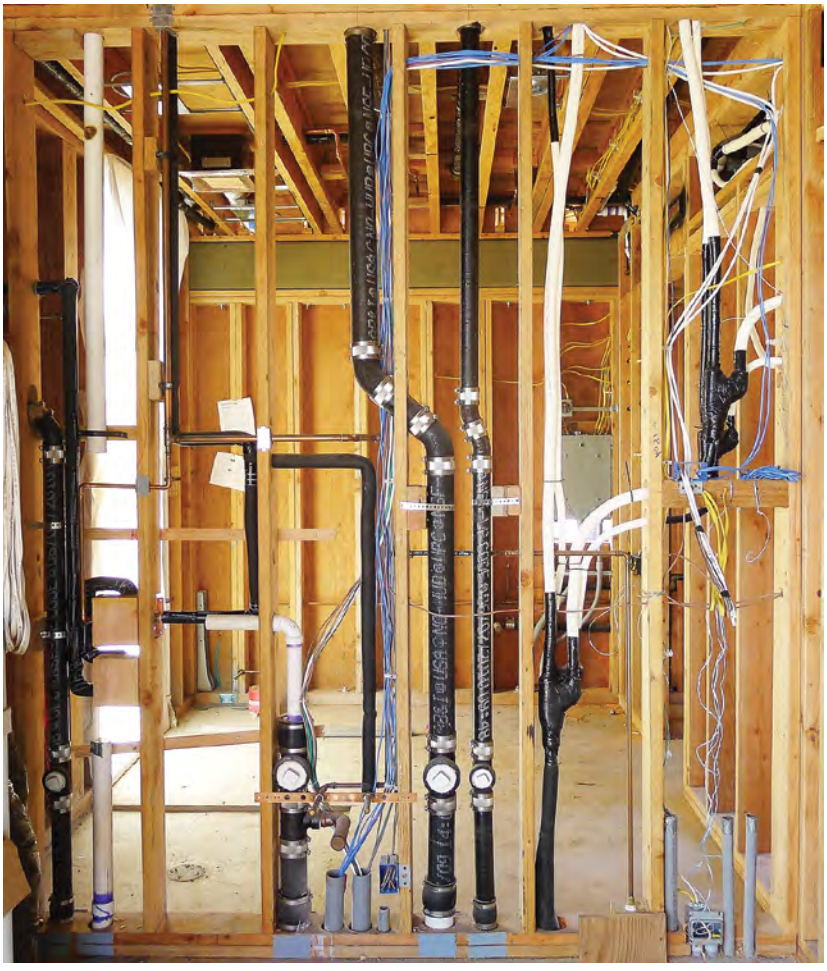


FIGURE 7.5
This plumbing wall is framed with 2 × 8 (38 × 184 mm) studs to provide adequate width for the plethora of building services routed within it, including cast iron and plastic DWV piping, insulated hot water and bare cold water copper supply piping, refrigerant piping for a distributed air conditioning system, communications wiring, and power wiring. *(Photo by Joseph Iano.)*

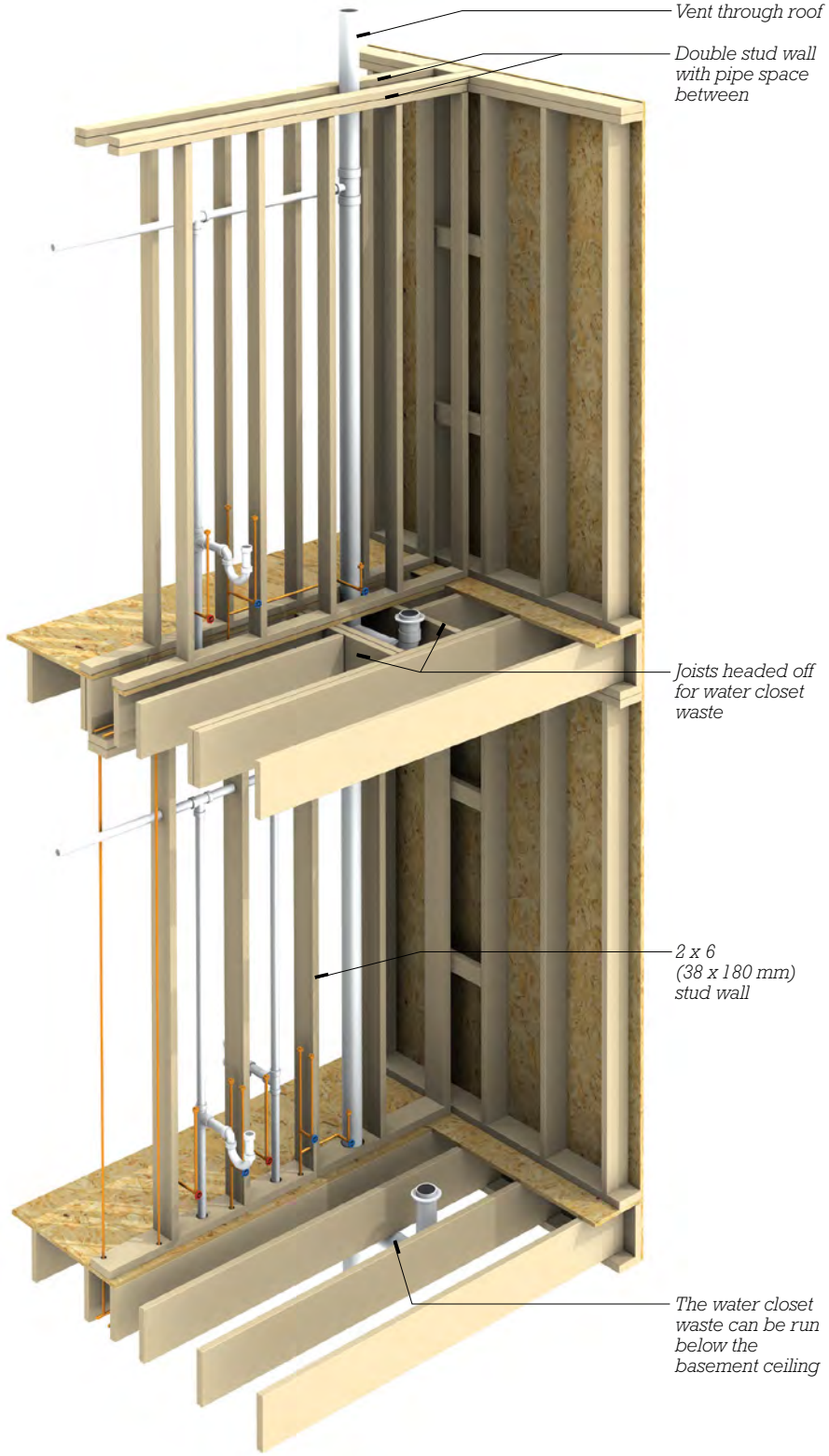


FIGURE 7.6

The plumber's work is easier and less expensive if the building is designed to easily accommodate piping. The "stacked" arrangement shown here, in which a second-floor bathroom and a back-to-back kitchen and bath on the first floor share the same vertical runs of pipe, is economical and easy to rough in, compared with plumbing that does not align vertically from one floor to the next. The double wall framing on the second floor allows plenty of space for the waste, vent, and supply pipes. The second-floor joists are located to provide a slot through which the pipes can pass at the base of the double wall, and the joists beneath the water closet (toilet) are headed off to house its waste pipe. The first floor shows an alternative type of wall framing using a single layer of deeper studs, which must be drilled to permit horizontal runs of pipe to pass through, as in Figure 7.5.

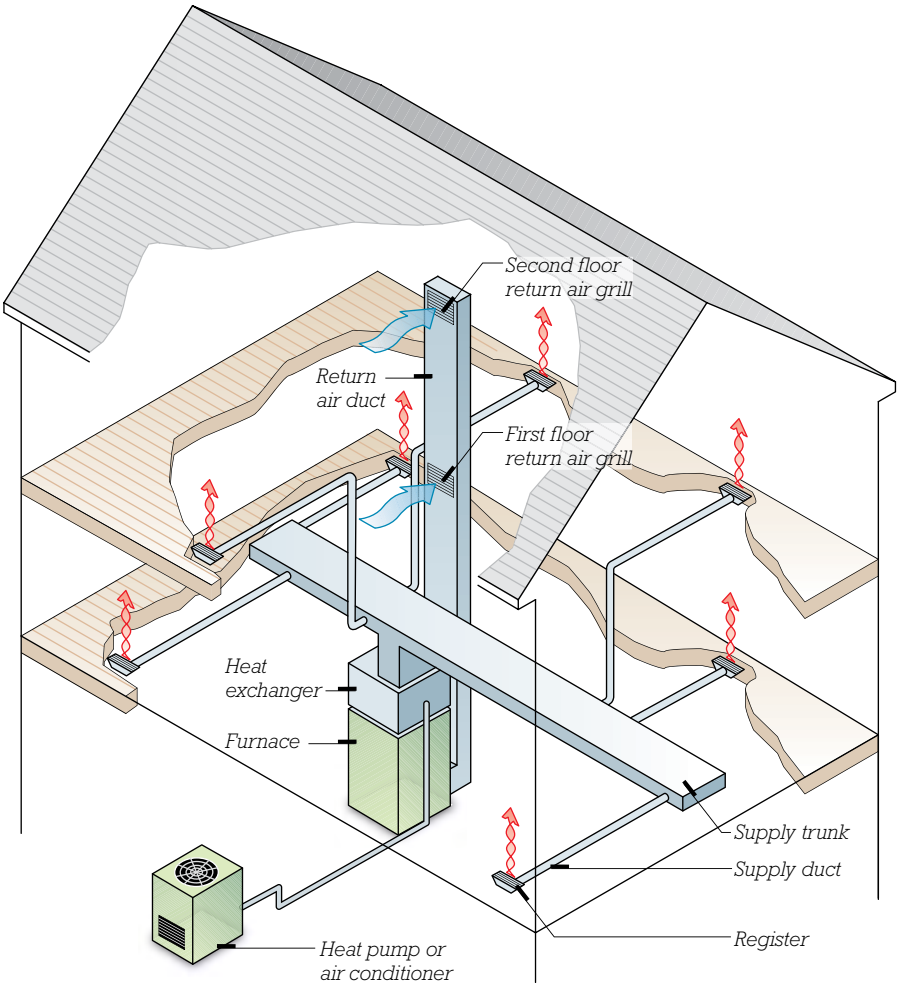


FIGURE 7.7
A forced-air system in a two-story building with a basement. The furnace is in the basement. It burns gas or oil, or uses electric resistance heating to warm a heat exchanger that creates warm air. It blows the warm air through sheet metal supply ducts to registers in the floor near the exterior walls. The air returns to the furnace through a centrally located return air duct that has a return air grill near the ceiling on each floor. With the addition of a heat pump or air conditioner, this system can deliver cool, dehumidified air during the warm months. Not shown in this diagram are additional parts of the *heating, ventilating, and air conditioning* (*HVAC*) system needed for introducing minimum quantities of fresh outside air into the building interior and for providing dedicated exhausts at bathrooms and kitchens.

FIGURE 7.8
The installation of this hot air furnace and air conditioning unit is almost complete, needing only electrical connections. The metal pipe running diagonally to the left carries the exhaust gasses from the oil burner to the masonry chimney. The ductwork is insulated to prevent moisture from condensing on it during the cooling season and to prevent excessive losses of energy from the ducts. *(Photo by Edward Allen.)*

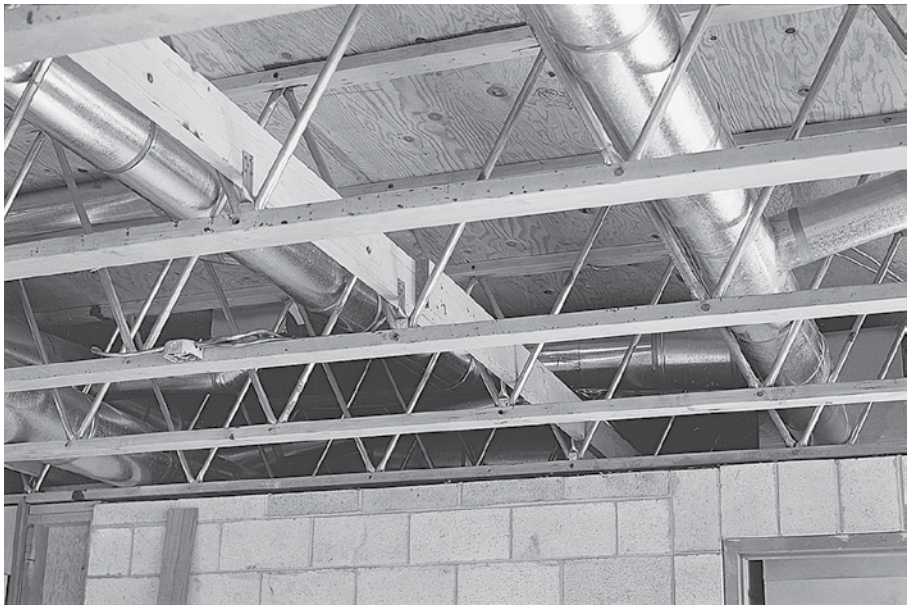


FIGURE 7.9
Ductwork and electrical wiring are installed conveniently through the openings in these floor trusses, making it easy to apply a finish ceiling if desired. The 2 × 6 that runs through the trusses in the center of the photograph is a bridging member that restrains the trusses from buckling. *(Courtesy of Trus Joist Corporation.)*

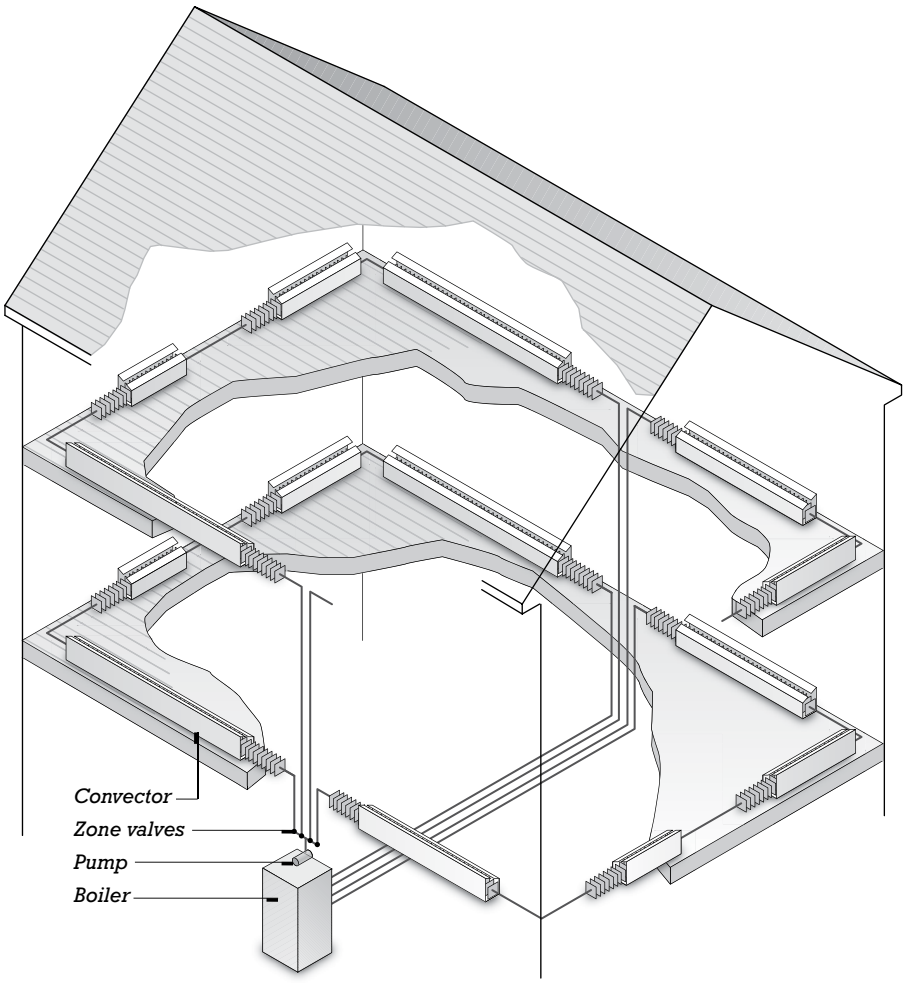


FIGURE 7.10
A hydronic heating system. The boiler burns gas or oil, or uses electric resistance heating to heat water. Pumps circulate the water through pipes that lead to convectors in various zones of the building. Inside each convector, a pipe heats closely spaced metal fins that warm the air in the room. The sheet metal convector covers are shown schematically and have been cut away in this drawing to reveal the metal fins.

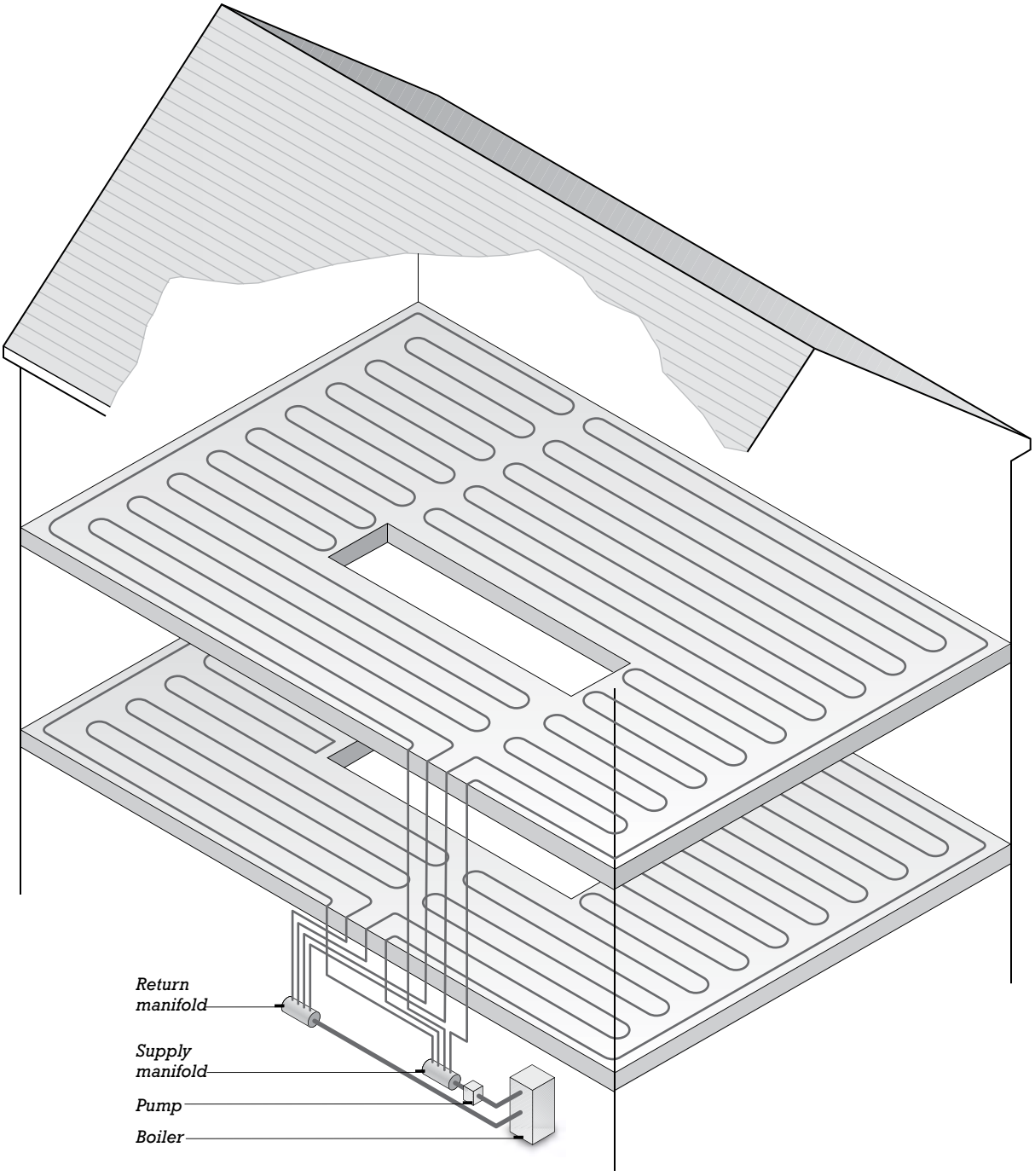


FIGURE 7.11
The radiant heating system in this two-story building delivers heat through hydronic tubes that warm the floors. There are four zones, two upstairs and two downstairs. Water is heated in a boiler and pumped through a supply manifold, where thermostatically controlled valves control the water flow to each of the zones.

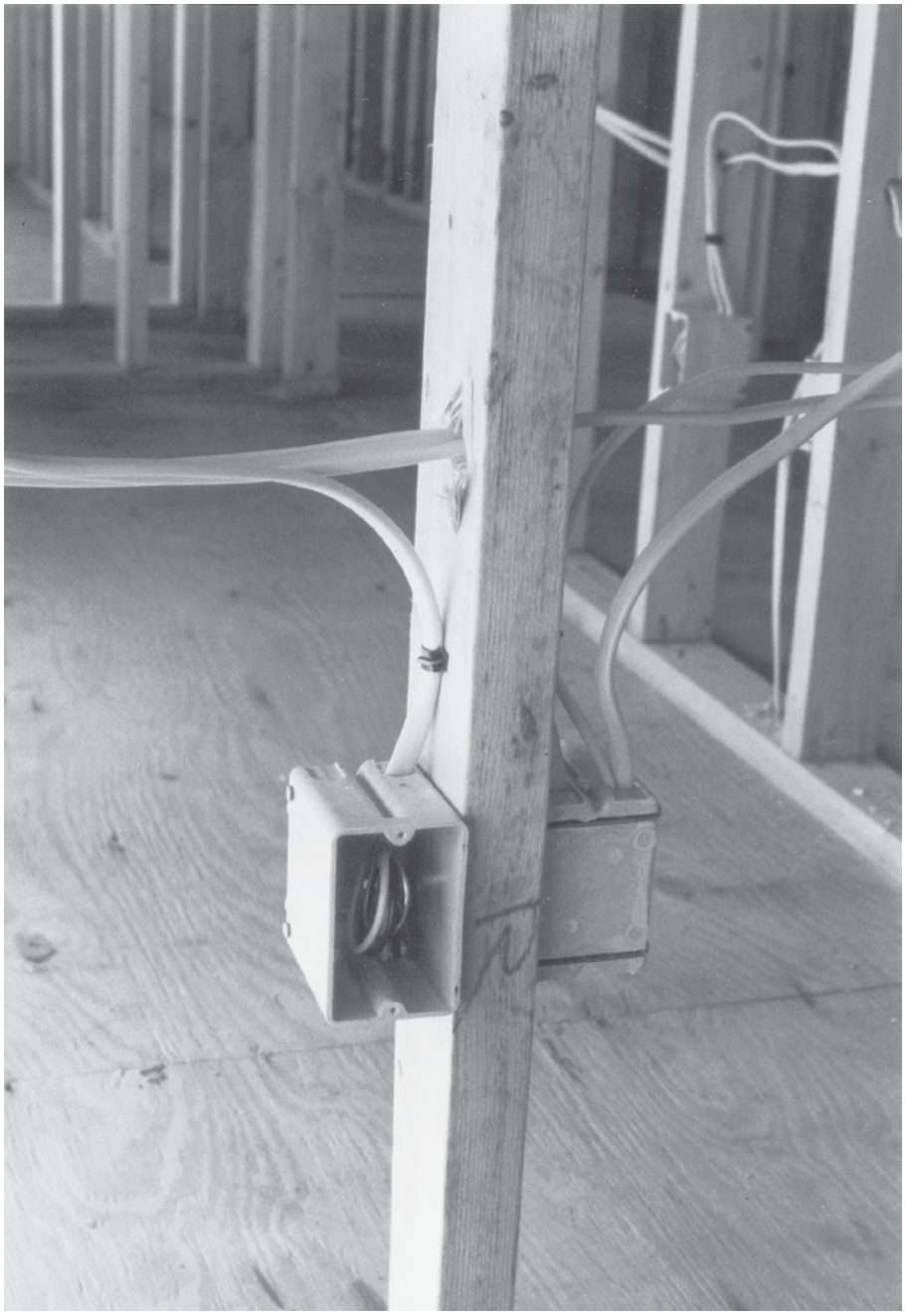


FIGURE 7.12
The electrician begins work by nailing metal or plastic fixture boxes to the framing of the building in the locations shown on the electrical plan. Then holes are drilled through the framing, and the plastic-sheathed cable, which houses two insulated copper conductors and an uninsulated ground wire, is pulled through the holes and into the boxes, where it is held by insulated staples driven into the wood. After the interior wall materials are in place, the electrician returns to connect outlets, lighting fixtures, and switches to the wires and the boxes and to affix cover-plates to finish the installation. *(Photo by Edward Allen.)*

COMPLETING THE BUILDING ENCLOSURE

The walls, roofs, and other surfaces of a building that separate the indoors from the outdoors are called the *building enclosure* or *building envelope*. The building enclosure controls the flow of heat, air, liquid water, and water vapor between the interior and exterior, as well as performing other important functions. Well-designed and carefully constructed enclosure assemblies help keep a building cooler in summer and warmer in winter by retarding the passage of heat and air through the exterior surfaces of the building. They help keep the occupants of the building more comfortable by moderating the temperatures of the interior surfaces of the building and reducing drafts. They reduce the building energy consumption for heating and cooling to a fraction of what it otherwise would be. And they prevent the harmful accumulation of moisture within the exterior walls, roof, and other exterior assemblies. For a more in-depth discussion of the functions of the building enclosure, see Chapter 16.

Insulating the Building Frame

Thermal insulating materials resist the conduction of heat. *Thermal insulation* is added to virtually all buildings to limit winter heat loss and/or summer cooling loads. A material's resistance to the conduction of heat is measured as *thermal resistance*, abbreviated as *R-value*, or, in metric units, as *RSI-value* (or in many cases, also simply as R-value). A material with a higher R-value is a better insulator than one with a lower R-value. Figure 7.13 lists common thermal insulating materials used in wood light frame buildings and some of their characteristics. *Glass fiber batts* are the most popular, but all of those listed find use.

Type	Material	R-Value[a]	Combustibility	Advantages and Disadvantages
Batt	Glass fiber or mineral wool	3.2–4.3 *22–30*	Noncombustible; facings are combustible	Low in cost, easy to install
Batt	Treated cotton	3.0–3.7 *21–26*	Limited combustibility	High percentage of recycled materials content
Spray fibers with binder	Glass and mineral fiber, treated cellulose	3.1–4.0 *22–28*	Same as above	Low in cost
Foamed in place, high density	Polyurethane	5.0–7.0 *35–49*	Combustible, gives off toxic gasses when burned[b]	High R-value, seals against air leakage, vapor impermeable
Foamed in place, low density	Polyicynene, polyurethane	3.6–4.0 *25–28*	Same as above	Seals against air leakage, vapor permeable
Rigid board	Expanded polystyrene (EPS) foam	3.6–4.2 *25–29*	Same as above	Low vapor permeance, can be used in contact with soil
Rigid board	Extruded polystyrene (XPS) foam	5 *35*	Same as above	Lower vapor permeance, higher compressive strength, and lower moisture absorption than EPS
Rigid board	Polyisocyanurate foam	5–6 *35–42*	Same as above	High R-value, compatible with asphaltic roof membranes, high cost
Semirigid board	Mineral fiber	3.6–4.2 *25–30*	Noncombustible	Moderate cost, vapor permeable

[a] R-values are per unit of thickness, expressed first in inch-pound units of ft^2-hr-°F/BTU-in. and second in metric units (italicized) of m^2-°K/W-m. For example, for an insulation material with R-values of 5 ft^2-hr-°F/BTU-in. (35 m^2-°K/W-m), 3 inches (76 mm) of the material would have a total insulation value of 5 ft^2-hr-°F/BTU-in. × 3 in. = R-15 or 35 m^2-°K/W-m × 0.076 m = RSI-2.7.

[b] Though all plastic foams are combustible, resistance to ignition and tendency for flame propagation vary among available products.

FIGURE 7.13
Commonly used thermal insulation materials. The R-values per equal thickness offer a direct means of comparing the relative effectiveness of the different types.

Batt insulation comes in 16-inch or 24-inch (406 or 610 mm) widths. It is installed by inserting the insulation between framing members and is held in place either by friction or, if the insulation has a paper or foil facing, by stapling the facing to the framing (Figure 7.14). Loose fill insulation is blown into attic floors or, in insulation retrofits, into wall cavities through holes drilled through the exterior siding or interior wallboard or plaster. Spray fiber insulation is blown from a nozzle (Figure 7.15). A light spray of water activates a binder that adheres the insulation in place and prevents settlement. Foamed-in-place insulation usually consists of two components sprayed or injected into place, where they react chemically to expand and adhere to the surrounding surfaces (Figure 7.16). Rigid and semirigid board insulation are nailed in place over wood framing, or when used around foundations, adhered in place (Figure 5.12). Plastic foam insulation, both spray foam and rigid board, is combustible and releases toxic gasses when it burns. Where these materials face the building interior, most must be covered with gypsum wallboard or some other material that will delay the onset of combustion while occupants exit the building.

Increasing Levels of Thermal Insulation

The colder the climate, the greater the amounts of insulation required in the building enclosure to avoid wasteful energy loss. According to current energy code standards, a wall framed with 2 × 4 (38 × 89 mm) studs and

(*a*)

(*b*)

(*c*)

(*d*)

(*e*)

FIGURE 7.14

(*a*) Installing a polyethylene vapor retarder over glass fiber batt insulation using a staple hammer, which drives a staple each time it strikes a solid surface. The batts are unfaced and stay in place between the studs by friction. (*b*) Stapling paper-faced batts between roof trusses. (Better practice is to staple the paper facing to the face of the framing member, rather than to its side as seen here.) (*c*) Placing unfaced batts between ceiling joists in an existing attic. Vent spacers should be used at the eaves (see Figure 6.7). (*d*) Working from below to insulate a floor over a crawlspace. Batts in this type of installation may be retained in place by pieces of stiff wire cut slightly longer than the distance between joists and sprung into place at frequent intervals below the insulation. (*e*) Insulating crawlspace walls with batts of insulation suspended from the sill. The header space between the joist ends has already been insulated. *(Courtesy of Owens-Corning Fiberglas Corporation.)*

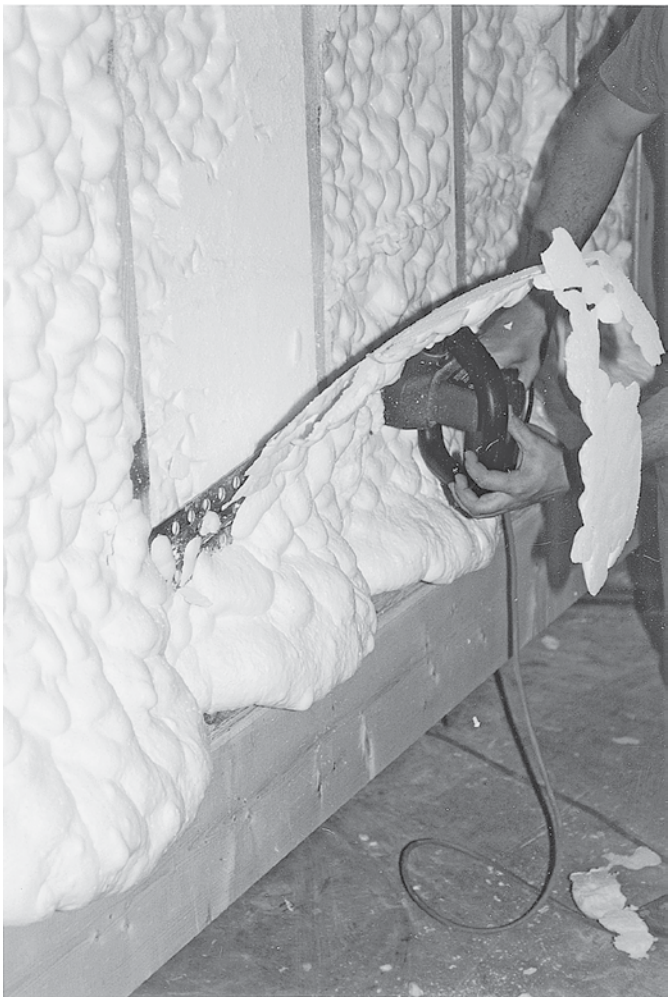
Figure 7.15
Blowing loose-fill glass fiber insulation into a ceiling below an attic. A vapor retarder was installed on the bottom side of the joists and then a gypsum board ceiling, which supports the insulation. Vent spacers were installed at the eaves to prevent the insulation from blocking eave vents. *(Courtesy of Owens-Corning Fiberglas Corporation.)*

filled with R-13 (RSI-2.3) glass fiber batt insulation is adequate for residential buildings in only the southernmost portions of the continental United States and Hawaii. To achieve higher insulation values, the wall can be framed with 2 × 6 (38 × 140 mm) studs and insulated with thicker batts, and/or rigid or semirigid insulation can be added to one side or the other of the wall (Figure 7.17).

The effective thermal resistance of an enclosure assembly depends on the combined properties of the materials within it. For example, at the left in Figure 7.17, a 2 × 6 (38 × 140 mm) framed wall with R-20 (RSI-3.5) batt insulation has an effective insulation value of no more than approximately R-18 (RSI-3.2). This reduction occurs because of *thermal bridging* at the wood studs. That is, because wood is a relatively poor insulation material, more heat flow occurs through these parts, and the wall's overall insulating effectiveness is reduced. At the right in Figure 7.17, exterior insulation is added to the wall. Because this *continuous insulation* is uninterrupted, it mitigates the detrimental effects of thermal bridging. Adding continuous exterior insulation also raises the temperature of the exterior sheathing within the assembly, reducing the risk of condensation on the back side of the sheathing in cold conditions. In the coldest climate zones, continuous insulation is required in all exterior walls.

Walls may be insulated to levels greater than those illustrated in Figure 7.17, either to meet code

(*a*)



(*b*)

FIGURE 7.16

(*a*) Spraying a low-density polyicynene foam insulation between studs of a wood light frame building. At the time of spraying, the components are dense liquids, but they react immediately with one another to produce a low-density foam, as has already occurred at the bottom of the cavity. The foam in the cavity to the right has already been trimmed off flush with the studs. (*b*) Trimming off excess foam with a special power saw. *(Courtesy of Icynene, Inc., Toronto, Canada.)*

requirements in colder climate zones, or, where desired, to improve the energy efficiency of the building beyond code minimums. For example, the enclosure thermal efficiency of a building designed to the *Passive House* standard must be high enough such that no major heating or cooling systems are required to maintain the building at comfortable temperatures. The majority of the heat required to keep a Passive House building warm comes from the body heat of its occupants, waste heat from electrical equipment, and solar gains. Figure 7.18 illustrates two possible ways to achieve high insulation values in a wood light frame wall. The *superinsulated* wall on the right has an insulation value in the range of what may be required in a Passive House project in a cold climate.

Heat loss due to thermal bridging across the wall cavity is also reduced with attention to framing details where extra framing members are typically inserted into the wall.

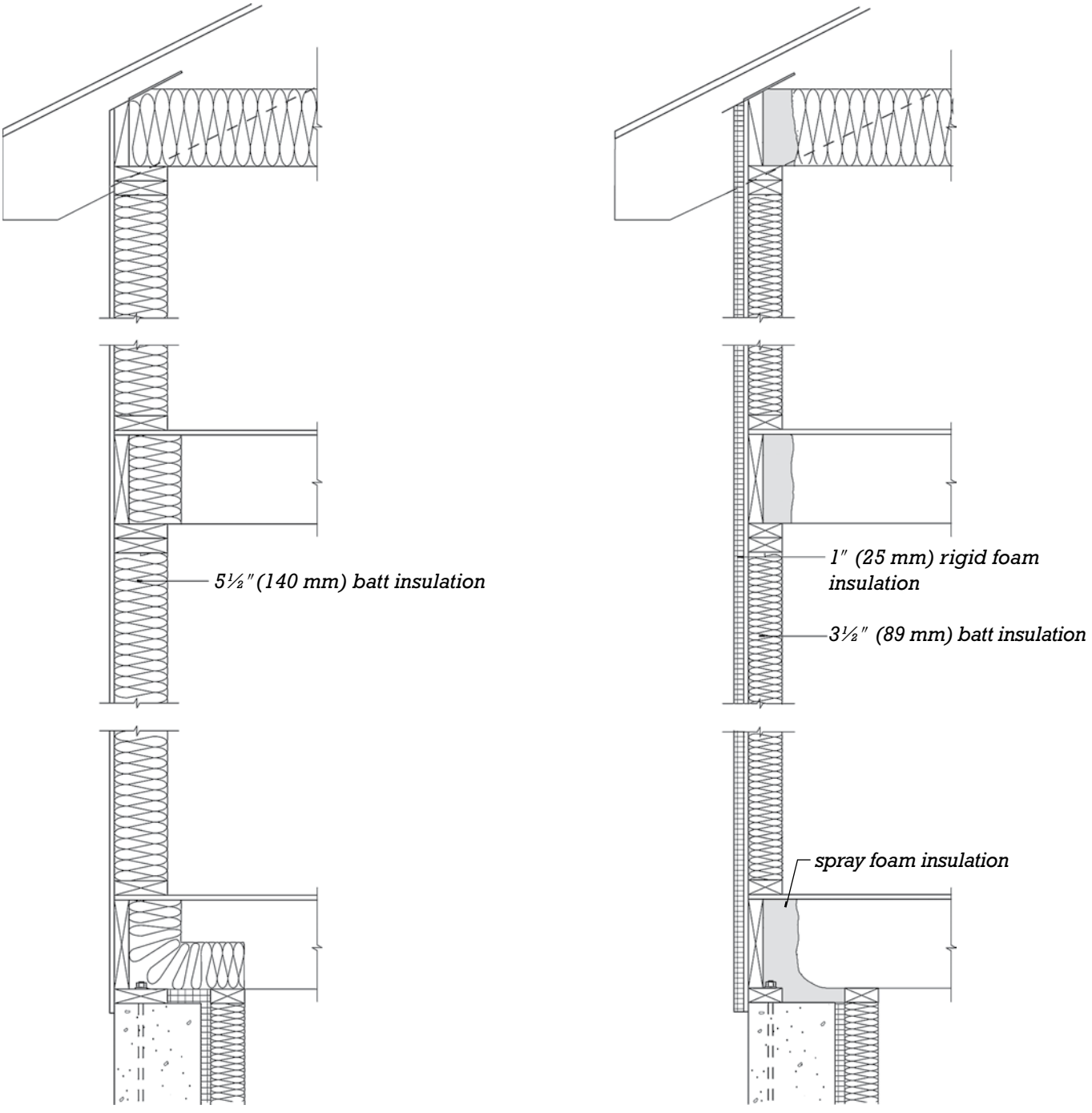
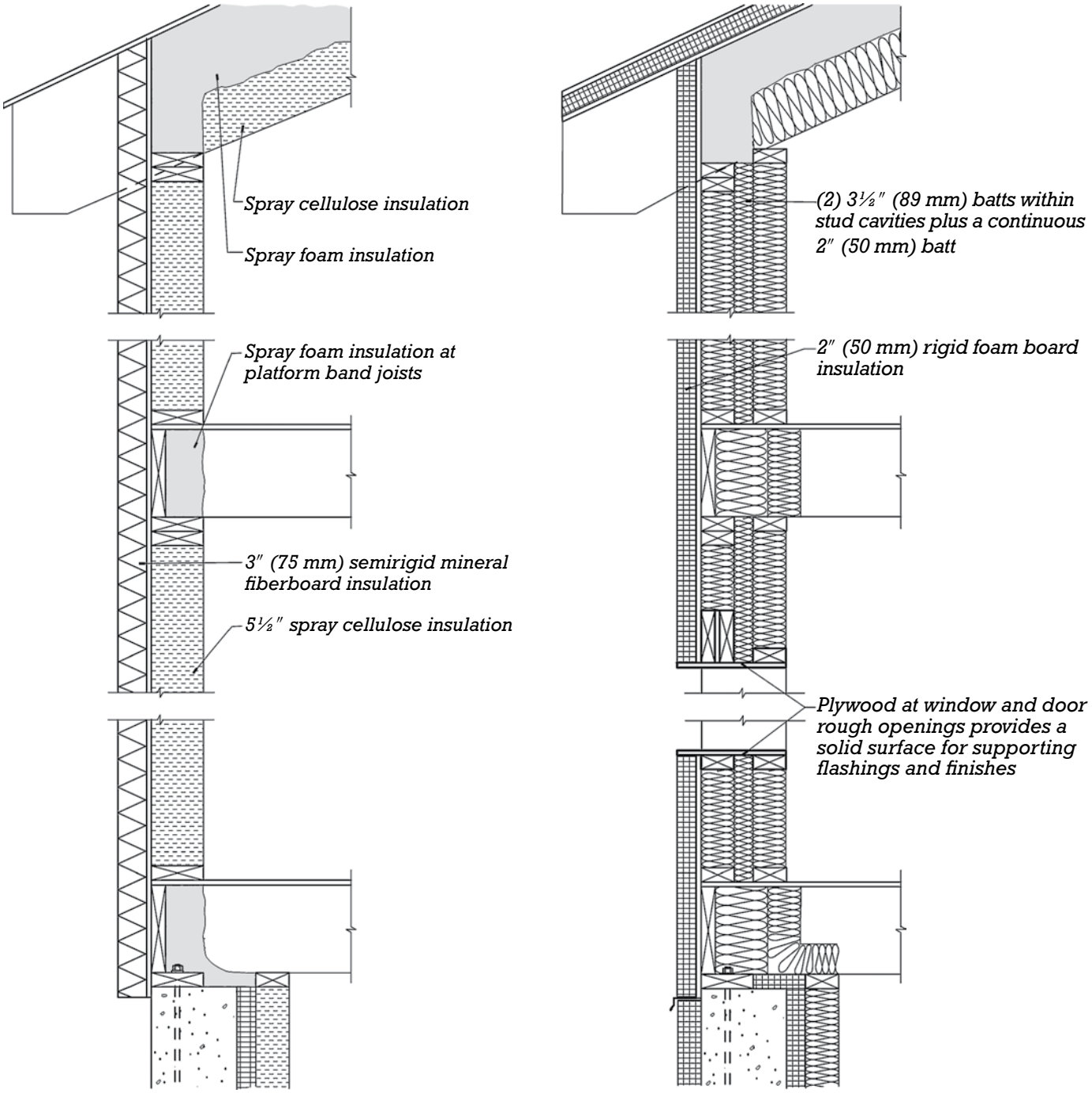


Figure 7.17

***Left*, a 2 × 6 (38 × 140 mm) framed wall with R-20 (RSI-3.5) glass fiber batt insulation. Accounting for the thermal bridging of the wood framing, the wall has an effective insulation value in the range of R-14 to R-18 (RSI-2.4 to RSI-3.2). *Right*, a 2 × 4 (38 × 89 mm) framed wall with R-15 (RSI-2.6) batt insulation and R-5 (RSI-0.88) extruded polystyrene foam; continuous exterior insulation achieves effective insulation values in the same range as the 2 × 6 framed wall without continuous insulation. Vapor retarders have not been shown in this figure or in Figure 7.18.**



2 × 6 STUDS WITH CONTINUOUS INSULATION AND SPRAY-APPLIED CELLULOSE

DOUBLE-FRAMED SUPERINSULATED WALL

FIGURE 7.18

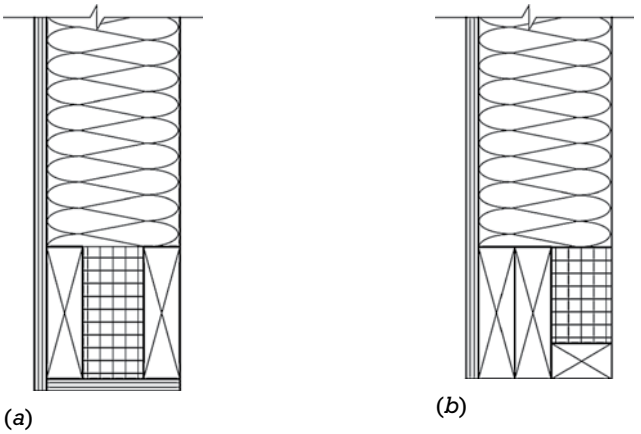
Two examples of wall assemblies that achieve insulation values exceeding current code requirements for any North American climate zone. *Left*, a 2 × 6 (38 × 140 mm) framed wall is insulated with spray-applied cellulose and a continuous 3-inch (76-mm) layer of semirigid mineral wool insulation on the outside of the sheathing. This assembly achieves an insulation value of approximately R-32 (RSI-5.6). *Right*, a double-framed wall with a total of 9 inches (229 mm) of glass fiber batts and a continuous 2-inch (51-mm) layer of rigid foam insulation. This wall attains a value of approximately R-42 (RSI-7.4). In this example, the outer framed wall is the bearing wall. Alternatively, an assembly such as this can be built with the inner framed wall as the loadbearing wall. This, in turn, allows the platform framing for floors and roofs to extend only so far as the inner wall, further reducing thermal bridging in these areas. However, this approach may also be more difficult and costly to construct.

Figures 7.19 and 7.20 illustrate details that reduce the area of solid framing at wall corners and headers over doors and window openings. Advanced framing techniques, discussed in Chapter 5, also significantly reduce thermal bridging in the wall frame.

Insulation continuity can also become compromised where ceiling insulation under a sloped roof must be compressed in the diminishing space between the roof sheathing and the top of the exterior wall, as can be seen in Figure 7.17. A raised-heel roof truss is one way to overcome this problem (Figure 7.21).

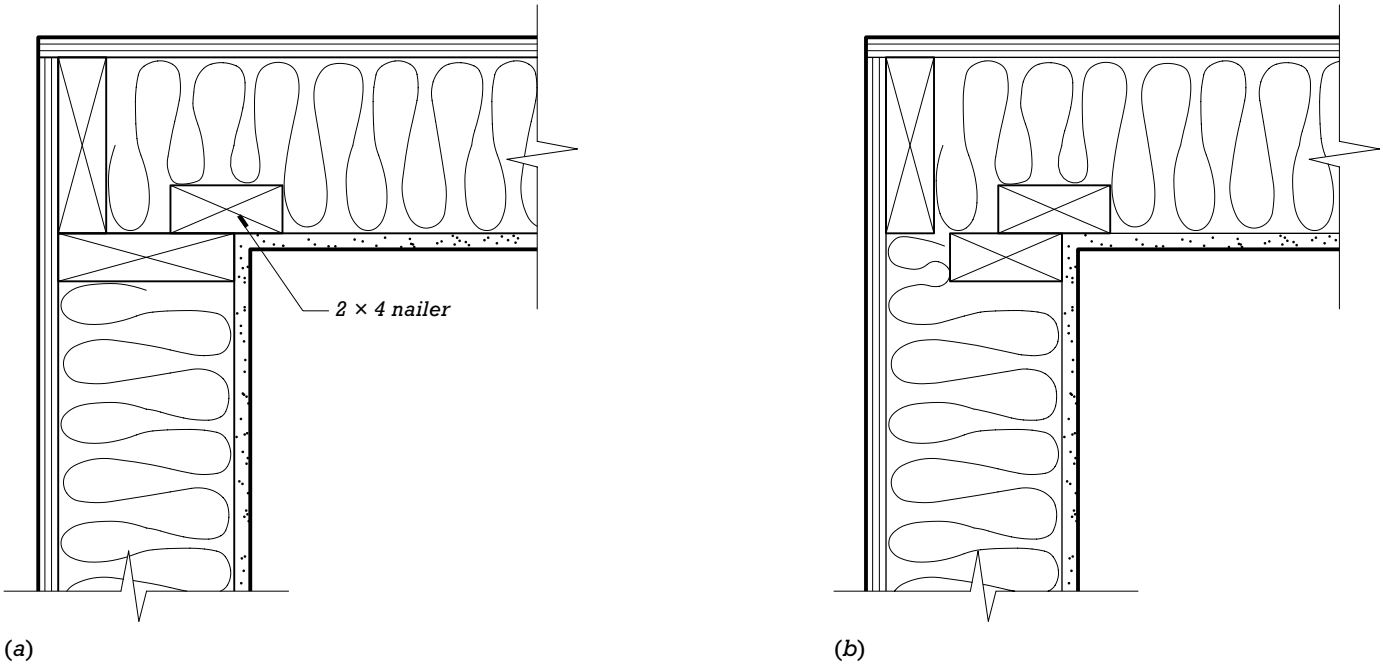
Radiant Barriers

In warmer regions, *radiant barriers* may be used in roofs and walls to reduce the flow of heat into the building. These are thin sheets or panels faced with a bright metal foil that blocks the transmission of infrared radiation (thermal radiation). Radiant barriers can be installed in various locations within the wall or roof. However, the reflective surface must face an airspace in order to function. In one configuration, radiant barriers are located close to the exterior side of the wall or roof assembly,



(*a*) (*b*)

FIGURE 7.19
Insulated headers for window and door openings that reduce thermal bridging in a 2 × 6 (38 × 140 mm) framed wall, shown in section view: (*a*) At the time the header is constructed, rigid foam insulation is sandwiched between the two members. Plywood nailed across the bottom of the headers allows for attachment of finishes. (*b*) A double header is installed flush with the exterior. Later, rigid foam insulation can be added on the interior side. A nailer provides attachment for wall finishes.



(*a*) (*b*)

FIGURE 7.20
Insulated corner details that minimize thermal bridging in a 2 × 6 (38 × 140 mm) framed wall, shown in plan view: (*a*) Each wall frame ends with a full 2 × 6 stud. A single 2 × 4 nailer is added to accept fasteners from the interior wall finish. (*b*) For even greater thermal efficiency, one wall frame ends with a 2 × 4 (38 × 89 mm) stud flush with the interior surface. In this arrangement, no corners studs fully bridge the insulation cavity from inside to outside.

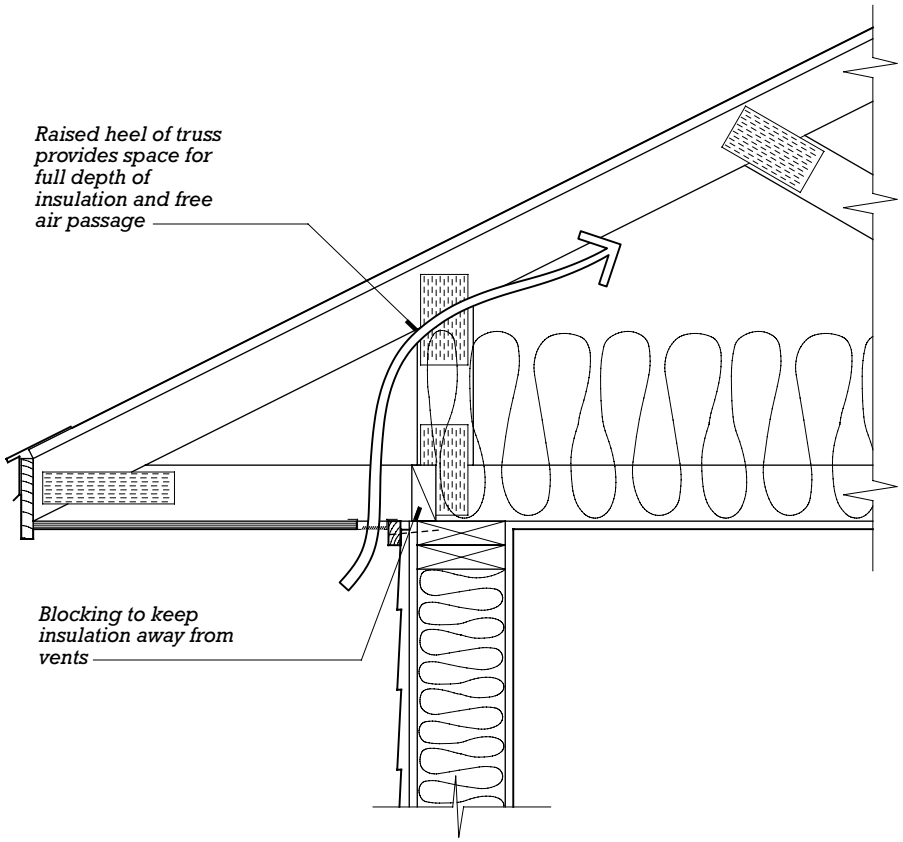


FIGURE 7.21
A raised-heel roof truss provides plenty of space for attic insulation at the eave.

in a ventilated airspace. The radiant barrier reflects the very high temperatures experienced by the outermost skin of the building, and the ventilated space convectively exhausts accumulated heat. Alternatively, a radiant barrier may be attached to the underside of roof framing in an attic. In this location, the barrier is equally effective at preventing the radiation of heat downward. A potential shortcoming of radiant barriers is their loss of effectiveness over time if the reflective surface becomes dulled by dust, grime, or corrosion.

Vapor Retarders

A *vapor retarder* is a material used to prevent water vapor (water in a gas state, or humidity) from diffusing into an insulated assembly where it may condense into liquid. In the International Residential Code, vapor retarders are grouped accordingly to their relative resistance to water vapor diffusion. Class I vapor retarders are the most resistant; that is, they have the lowest *vapor permeance*. Class II and III retarders are each increasingly permeable. Because of their very low vapor permeance, Class I vapor retarders may also be called *vapor barriers*.

Where vapor retarders are used, they are placed on the warm (usually interior) side of the insulation. Polyethylene plastic sheet, a Class I vapor retarder, is stapled to the face of wood framing after the insulation has been installed in the framing cavities (Figure 7.14*a*). To further improve its performance (as well as to control air leakage), the edges of the sheets are lapped and taped or sealed, and penetrations at electrical outlets, plumbing, and other such elements are carefully sealed. Asphalt-coated kraft paper facing available with many batt insulation products is a Type II vapor retarder (Figure 7.14*b*). Latex paint applied over conventional interior gypsum wallboard is an example of a Class III vapor retarder. Some vapor retarder products with proprietary formulations are capable of adjusting their vapor permeance to suit varying conditions within the wall. For example, under normal conditions, vapor diffusion into the wall is resisted. But if a wall assembly becomes unsuitably damp, the membrane permeability increases, allowing moisture to evaporate and the wall to dry.

The importance of the vapor retarder in an insulated assembly increases in colder climates. For example, the International Residential Code requires Type I or II vapor retarders for buildings in roughly the upper half to two-thirds of the continental United States. But climate conditions are not the only consideration. For example, where exterior walls are designed to be tolerant of high rates of vapor diffusion without harmful condensation, more permeable Type III vapor retarders may

Sustainability and Insulation Materials for Wood Light Frame Construction

Energy Performance

Thermal insulation in walls, roofs, and other parts of the building enclosure is perhaps the most cost-effective, planet-saving material used in buildings.

- Insulation increases occupant comfort.
- Insulation reduces the energy consumed to heat and cool buildings to a fraction of what it would otherwise be.
- The cost to insulate buildings gets paid back through energy savings many times over the life of the building.

	Unfaced glass fiber batt	Light-density mineral wood board	Closed-cell spray polyurethane foam
Nonrenewable primary energy consumption	12 MJ (14,000 BTU)	38 MJ (36,000 BTU)	130 MJ (130,000 BTU)
Global warming potential	1.2 kg (2.6 lb) CO_2 eq.	2.8 kg (6.2 lb) CO_2 eq.	34 kg (75 lb) CO_2 eq.
Fresh water consumption	3.5 L (0.92 gal)	0.87 L (0.23 gal)	1100 L (280 gal)

Building and Material Life-Cycle Impacts

- Environmental impacts for three insulation types are tabulated below. All are based on cradle-to-grave EPDs, for 1 m² (10.8 sf) of insulation with a thermal resistance of RSI-1 (R-5.7), over a 60-year life span:

Material and Production Attributes

- Glass fiber insulation may contain up to 40 percent recycled material, and slag fiber insulation up to 70 percent. Rock wool insulation may include recycled slag fibers as well.

be used, or no vapor retarder may be needed at all. Or, where interior spaces have unusually high humidity (such as a swimming pool enclosure), vapor retarders with lower than normal vapor permeance may be needed. In the National Building Code of Canada, the insulated enclosure of small buildings must have vapor retarders comparable in performance to International Residential Code Class I or II materials.

In mixed or hot climates, the use of vapor retarders should be approached with caution, as they can lead to the unintended entrapment of water within the wall. For example, in air-conditioned buildings in hot, humid climates, interior materials such as vinyl wallpaper can act as vapor retarders on the cold side of the wall, leading to condensation and mildew growth behind the wallpaper.

Air Barriers

Air barriers control the leakage of air through the building enclosure. They significantly reduce building energy consumption and help protect enclosure assemblies from moisture condensation by restricting the infiltration of humid air.

Air barriers appear in some form in all insulated enclosures. Housewraps (discussed in Chapter 6) applied over exterior sheathing are one common way to incorporate an air barrier into wood light frame buildings. Or, when plastic sheeting used as a vapor retarder is carefully sealed against air leakage, it can function as an air barrier. Water-resistive barriers that are applied as fully adhered sheets or as liquids that cure in place perform very well as air barriers, because air cannot travel beneath these materials from one potential leakage point to another.

The *airtight drywall approach* (*ADA*) relies on the gypsum wallboard (drywall) panels used to finish interior walls and ceilings to create an effective air barrier (Figure 7.22). Careful attention must be given to details of construction with this method: Potential air leakage paths around the edges of gypsum panels and between abutting framing members must be sealed with compressible foam tape gaskets or joint sealants during the installation of these members. Gypsum board is applied to all the interior surfaces of the outside walls before the interior partitions

- Glass fiber, mineral fiber, and cellulose insulation products made with locally extracted and processed materials are available throughout many parts of North America.
- Plastic foam materials are made in large part from petroleum, a nonrenewable resource.
- Cellulose insulation is made from 85 percent recycled paper products, primarily newspaper.
- Cotton fiber insulation is made from up to 80 percent recycled content and up to 70 percent rapidly renewable resource (cotton).
- Lamb's wool is a rapidly renewable material and has very low embodied energy and global warming potential. However, these benefits are offset somewhat by the need to ship the material from New Zealand to North America.

Unhealthful Materials and Emissions

- The phenol-formaldehyde binder historically used in glass and mineral-fiber batts can release formaldehyde gas, a recognized carcinogen. Formaldehyde-free alternatives are now readily available.
- Spray-foam insulation products are mixed and applied on the building site and cure in place. Emissions during the application and curing of these materials are high, and protective equipment for workers is required.
- Long-term emissions and potential health impacts from installed spray foam insulation remain an area of ongoing study. The types of chemicals emitted and their concentrations vary among product types and formulations. Improper application that leads to uncured product can result in very high emissions for long periods of time after installation.
- Cotton fiber and lamb's wool insulation do not emit VOCs or chemical irritants.
- LEED, Living Building Challenge, and WELL Building Standard require testing of insulation products to verify that emissions from these materials do not exceed prescribed limits.

are framed, eliminating potential air leaks where these partitions intersect. And gaskets, sealants, or special airtight boxes are used to seal air leakage paths around electrical fixtures and other penetrations. A related system, *simple caulk and seal*, relies on the strategic application of joint sealants after framing and drywalling are complete to achieve much the same result as the ADA.

Energy codes require that residential buildings be detailed and constructed so as to limit air leakage through exterior enclosure assemblies. Some also require *blower door testing* once the insulation and air barrier components of the building enclosure are fully in place. In this test, a large fan is temporarily installed into an exterior door opening and used to pressurize the entire building interior to a specified level. Calculations are then performed to determine the rate of air leakage through the complete building enclosure. If the leakage rate exceeds that permitted, the sources of leakage are sought out and corrected until the enclosure is brought into compliance. The permitted rate of air leakage varies, with buildings in colder regions requiring more airtight enclosures than those in milder ones. For more information about vapor retarders and air barriers, see Chapter 16.

Infiltration and Ventilation

Reducing the flow of heat and air through the building enclosure reduces energy consumption. However, tightly constructed buildings may exchange so little air with the outdoors that if they are not adequately ventilated, indoor moisture, odors, and chemical pollutants can accumulate to intolerable or unhealthful levels. Opening a window to ventilate the dwelling is one way to introduce fresh air. But during heating or cooling seasons this wastes fuel. A better solution is a mechanical ventilation system designed to supply fresh air to interior spaces at a controlled and consistent rate. Such a ventilation system may be integrated with a forced-air heating or cooling system, or it may be dedicated solely to satisfying ventilation needs. For greater energy efficiency, a *heat recovery ventilator* or *energy recovery ventilator*—devices that recover heat from the air exhausted from the building and add it to the outside air that is drawn in—may be parts of such a system.

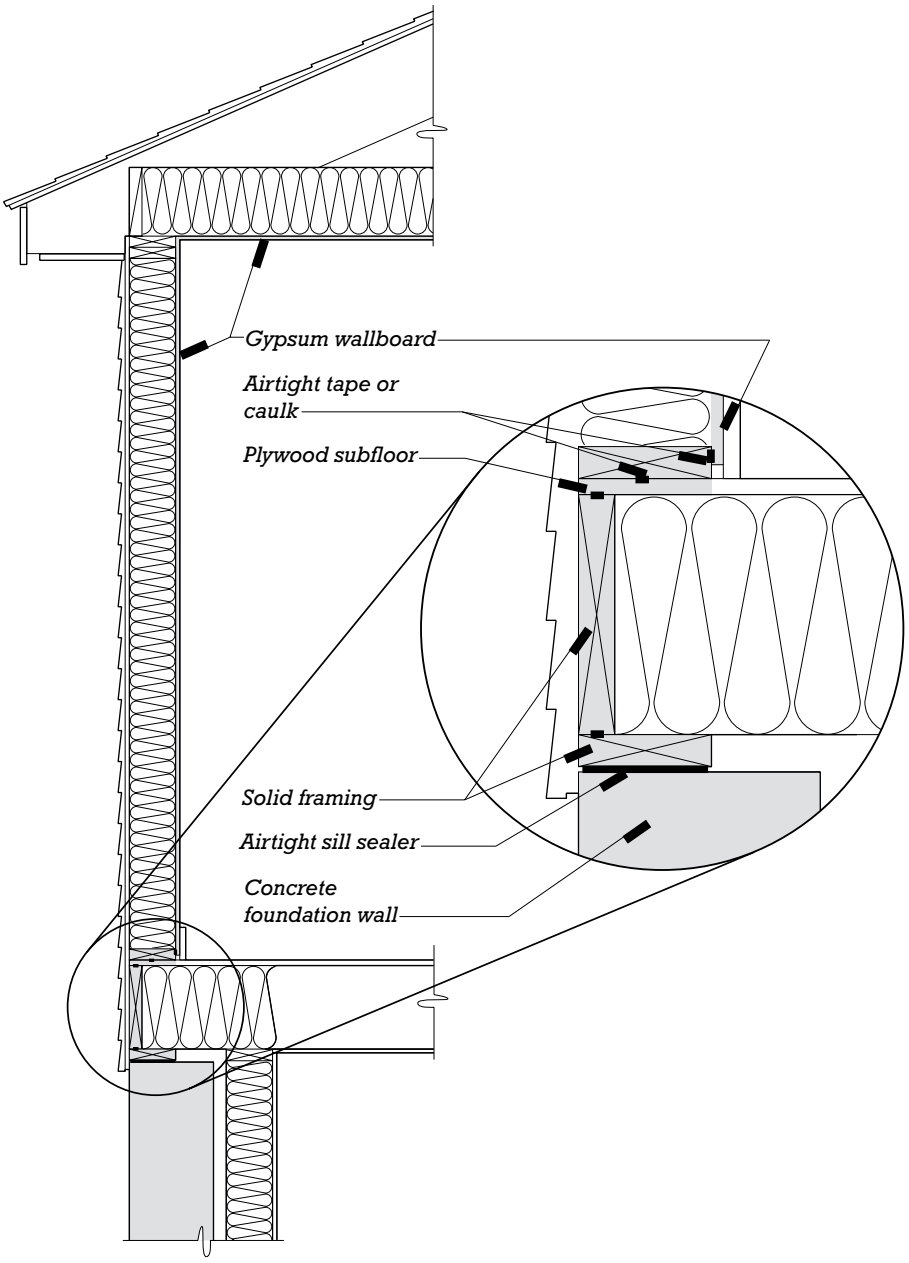


FIGURE 7.22
An air barrier system must form a continuous airtight boundary between the inside and outside of the building. In the ADA, the air barrier system is constructed of gypsum wallboard, wood framing members, and the concrete foundation wall (the shaded elements in the figure). Tapes and caulks (see the enlarged inset) are used to seal leakage paths between these components.

WALL AND CEILING FINISH

Gypsum-based plaster and drywall finishes have always been the most popular for walls and ceilings in wood frame buildings. Their advantages include substantially lower installed costs than any other types of finishes, adaptability to either painting or wallpapering, and, importantly, a degree of fire resistance that offers considerable protection to a combustible frame. *Three-coat gypsum plaster* applied to *wood strip lath* was the prevalent wall and ceiling finish system until the Second World War, when *gypsum wallboard* (also called *gypsum board* or *drywall*) came into increasing use because of its lower

material cost, more rapid installation, and utilization of less skilled labor. More recently, *veneer plaster* systems have been developed that offer surfaces of a quality and durability superior to those of gypsum board, often at comparable prices.

Plaster, veneer plaster, and gypsum board finishes are covered in detail in Chapter 23. Gypsum board remains the favored material for small builders who do all the interior finish work in a building themselves, because the skills and tools it requires are largely those of carpenters rather than plasterers. In geographic areas where there are plenty of skilled plasterers, veneer plaster captures a substantial share of the market. Almost everywhere in North America, there are subcontractors who specialize in gypsum board installation and finishing and who are able to finish the interior surfaces of larger projects, such as apartment buildings, retail stores, and rental office buildings, as well as individual houses, at highly competitive prices.

In most small buildings, all wall and ceiling surfaces are covered with plaster or gypsum board. Even wood paneling should be applied over a gypsum board backup layer, for increased fire resistance. In buildings that require fire walls between dwelling units or fire separation walls between areas with different uses, a gypsum board wall of the required degree of fire resistance can be installed, eliminating the need to employ masons to put up a wall of brick or concrete masonry (Figures 5.67 and 5.68).

Millwork and Finish Carpentry

Millwork (so named because it is manufactured in a planing and molding mill) includes all the wood interior finish components of a building. Millwork is produced from higher-quality wood than that used for framing: The softwoods used are those with fine, uniform grain structure and few defects, such as sugar pine, Ponderosa pine, or poplar. Flooring, stair treads, and other work intended for varnish or other transparent finish coatings are customarily made of hardwoods such as red and white oak, cherry, mahogany, or walnut, or of similar quality veneered hardwood plywoods. Millwork is not installed by the same carpenters, called rough framers, that erect the wood light frame structure but, rather, by *finish carpenters* using tools and methods more suitable to the fine workmanship required.

Quality standards for millwork are published by several North American trade associations. Three grades are defined: *Economy Grade* cabinetry and millwork is the most economical and represents the minimum expectation of quality. *Custom Grade* provides a more refined degree of control over the quality of materials, workmanship, durability, and installation and is the most commonly specified grade. *Premium* is the most expensive grade and is reserved for the very finest cabinets and millwork.

Millwork is manufactured and delivered to the building site at a low moisture content (about 10 percent), close to the condition that it will experience in the finished building. This is to prevent large dimensional changes from occurring between the time the millwork is manufactured and when it is put to use. However, as other finishing operations, such as plastering, gypsum board taping, and painting, come to conclusion, the humidity in the building may be quite high. So, to prevent the millwork materials from swelling or distorting, the building must dried out before the millwork is delivered to the construction site. Through some combination of ventilation and activation of the heating and air conditioning system, the interior spaces must be brought to a condition close to what will exist once the building is finished—a process that can take from several days to a week or more.

Interior Doors

Figure 7.23 illustrates five doors that fall into three general categories: Z-brace, panel, and flush. *Z-brace doors* are simple, utilitarian doors, mostly built on site, and used infrequently because they are subject to distortions and large amounts of moisture expansion and contraction in the broad surface of boards whose grain runs perpendicular to the width of the door. *Panel doors* were developed centuries ago to minimize dimensional changes and distortions caused by the seasonal changes in the moisture content of the wood. They are widely available in ready-made form from millwork dealers. *Flush doors* are smooth slabs with no surface features except the grain of the wood. They may be either solid core or hollow core. *Solid-core doors* consist of two veneered faces glued to a solid core of wood blocks or bonded wood chips (Figure 7.24). They are much heavier, stronger, and more resistant to the passage of sound than hollow-core doors and are also more expensive. In residential buildings, their use is usually confined to entrance doors, and because of their natural resistance to fire, doors between car garages and a residence. However, they are frequently installed throughout commercial and institutional buildings, where doors are subject to heavier use. *Hollow-core doors* have two thin plywood faces separated by an airspace. The airspace

Proportioning Fireplaces

Ever since fireplaces were first developed in the Middle Ages, people have sought formulas for their construction to ensure that the smoke from a fire will go up the chimney and the heat will go into the room, rather than the reverse, which is too often the case. To this day, there is little scientific information on how fireplaces work and how to design them. What we do have are measurements taken from fireplaces that seem to work reasonably well. These have been correlated and arranged into a table of dimensions (Figures B and C) that enables designers to reproduce the critical features of these fireplaces as closely as possible.

Several general principles are clear: The chimney should be as tall as possible. The cross-sectional area of the *flue* should be about one-tenth the area of the front opening of the fireplace. A *damper* should be installed to close off the chimney when no fire is burning and to regulate the passage of air through the *firebox* when the fire is burning (Figure A). A *smoke shelf* above the damper reduces fireplace malfunctions caused by cold downdrafts in the chimney. Splayed sides and a sloping back in the firebox reduce smoking and throw more heat into the room.

Starting from these general principles, two schools of thought have developed concerning how a fireplace should be shaped and proportioned. Most fireplaces in North America are built to the conventional standards tabulated here. Other designers, however, favor the rules for fireplace construction that were formulated by Count Rumford in the 1790s. These produce a fireplace with a taller opening and a shallower firebox than the conventional fireplace. The intention of the Rumford design is to attain a higher efficiency by throwing more radiant heat from the fire-warmed bricks at the back of the firebox to the occupants of the building.

Building codes place a number of restrictions on fireplace and chimney construction. Typically, these call for a 2-inch (51-mm) clearance between the wood framing and the masonry of a chimney or fireplace, and clearances to combustible finish materials around the opening of the fireplace as shown in Figure A. Also specified by code are the minimum thicknesses of masonry around the firebox and flue, the minimum size of the flue, the minimum extension of the chimney above the roof, and steel reinforcing for the chimney. A combustion air inlet must be provided to bring air from the outdoors to the base of the fire. For ready reference in proportioning fireplaces, use the values in Figures B and C. In most cases, the designer need not detail the internal construction of the fireplace beyond the information given in these dimensions, because masons are well versed in the intricacies of assembling a fireplace.

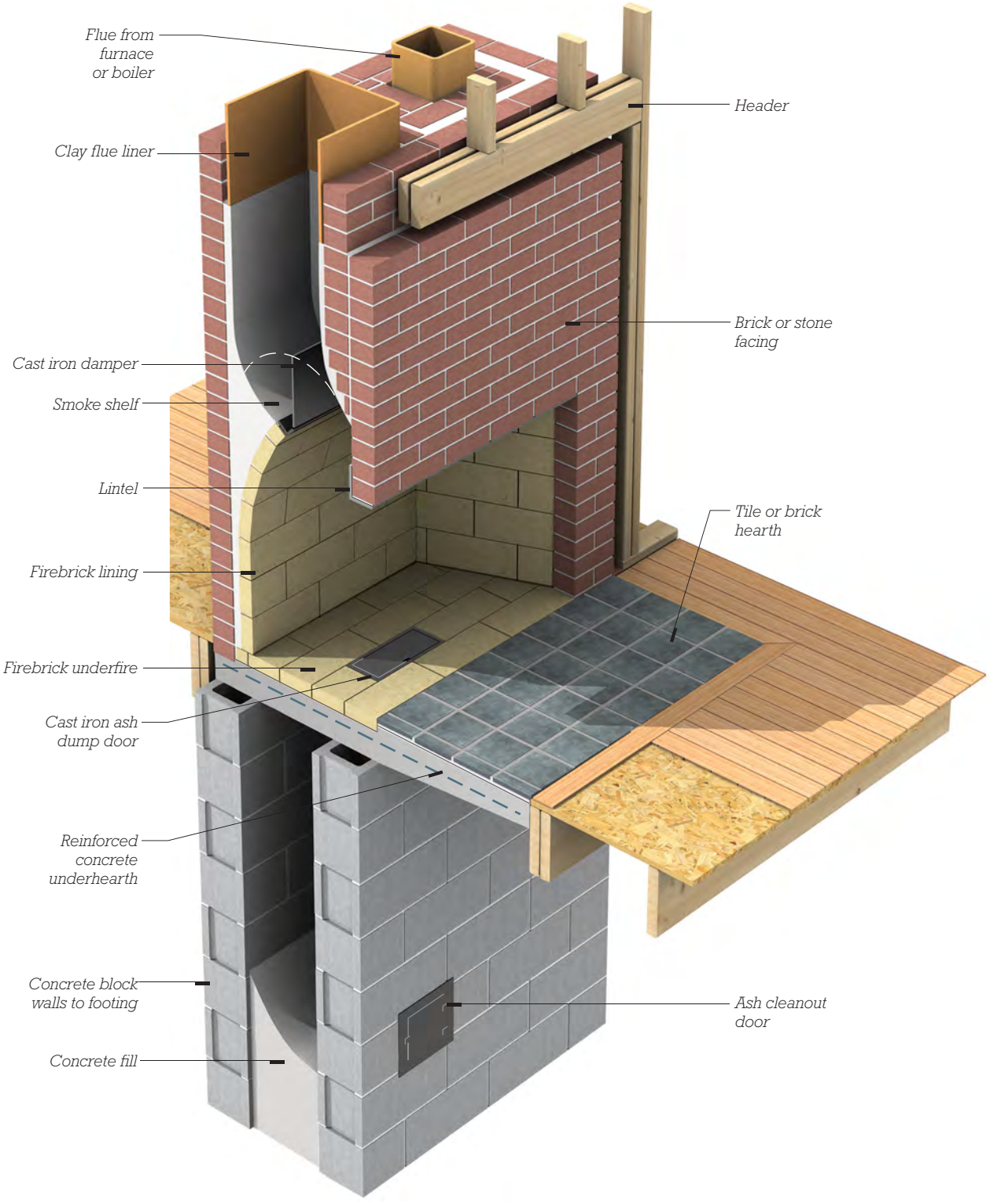
There are several alternatives to the conventional masonry fireplace. One is a steel or ceramic fireplace liner that takes the place of the firebrick lining, damper, and smoke chamber. Many of these products have internal passages that draw air from the room, warm it with the heat of the fire, and return it to the room. The liner is set onto the underhearth and built into a masonry facing and chimney by the mason.

Another alternative is the "package" fireplace, a self-contained, fully insulated unit that needs no masonry whatsoever. It is usually set directly on the subfloor and fitted with an insulated chimney of prefabricated metal pipe. It may be faced with any desired ceramic or masonry materials. Many package fireplaces are made to burn gas rather than wood.

A third alternative is a freestanding metal stove that burns wood, coal, or other solid fuel. Stoves are available in hundreds of styles and sizes. Their principal advantage is that they provide more heat to the interior of the building per unit of fuel burned than a fireplace. A stove requires a noncombustible hearth and a fire-protected wall that are rather large. The designer should consult the local building code at an early stage of design to be sure that the room is big enough to hold a stove of the desired dimensions.

Figure A

A cutaway view of a conventional masonry fireplace. Concrete masonry is used wherever it will not show, to reduce labor and material costs, but if hollow concrete blocks are used, they must be filled solid with grout. The damper and ash doors are prefabricated units of cast iron, as is a combustion air inlet in the hearth (not shown here) that connects with a sheet metal duct to an outdoor air intake. The flue liners are made of fired clay and are highly resistant to heat. The flue from the furnace or boiler in the basement slopes as it passes the firebox so as to adjoin the fireplace flue and keep the chimney as small as possible.


Flue from furnace or boiler
Header
Clay flue liner
Brick or stone facing
Cast iron damper
Smoke shelf
Lintel
Tile or brick hearth
Firebrick lining
Firebrick underfire
Cast iron ash dump door
Reinforced concrete underhearth
Concrete block walls to footing
Ash cleanout door
Concrete fill

Proportioning Fireplaces (continued)

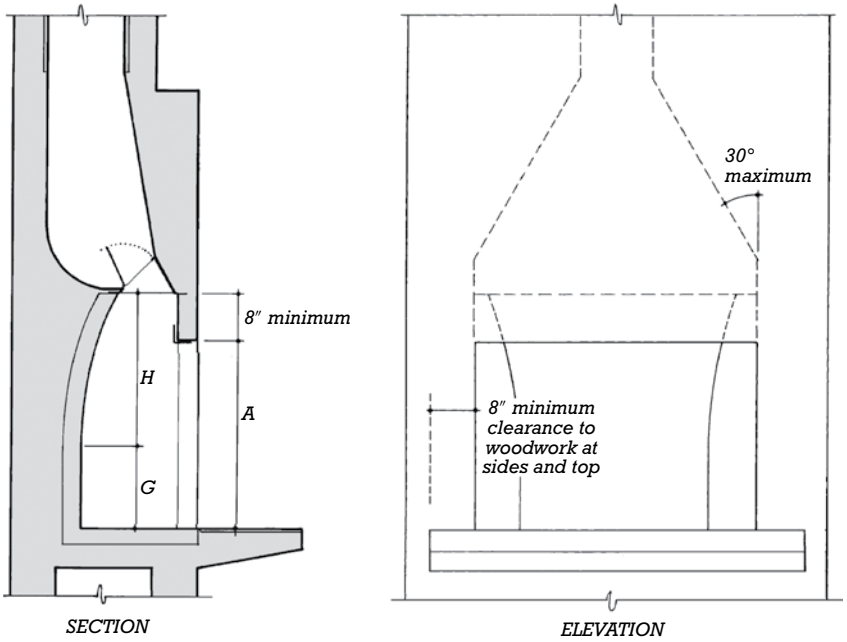


Figure B

The critical dimensions of a conventional masonry fireplace, keyed to the table in Figure C. Dimension *D*, the depth of the hearth, is commonly required to be 16 inches (405 mm) for fireplaces with openings up to 6 square feet (0.56 m²) and 20 inches (510 mm) if the opening is larger. The side extension of the hearth, *E*, is usually fixed at 8 inches (200 mm) for smaller fireplace openings and 12 inches (305 mm) for larger ones.

Fireplace Opening						Flue Lining	
Height (A)	Width (B)	Depth (C)	Minimum Backwall Width (F)	Vertical Backwall Height (G)	Inclined Backwall Height (H)	Rectangular (outside dimensions)	Round (inside diameter)
24" (610 mm)	28" (710 mm)	16 to 18" (405 to 455 mm)	14" (355 mm)	14" (355 mm)	16" (405 mm)	8½ × 13" (216 × 330 mm)	10" (254 mm)
28 to 30" (710 to 760 mm)	30"	16 to 18" (405 to 455 mm)	16" (405 mm)	14" (355 mm)	18" (455 mm)	8½ × 13" (216 × 330 mm)	10" (254 mm)
28 to 30" (710 to 760 mm)	36" (915 mm)	16 to 18" (405 to 455 mm)	22" (560 mm)	14" (355 mm)	18" (455 mm)	8½ × 13" (216 × 330 mm)	12" (305 mm)
28 to 30" (710 to 760 mm)	42" (1065 mm)	16 to 18" (405 to 455 mm)	28" (710 mm)	14" (355 mm)	18" (455 mm)	13 × 13" (330 × 330 mm)	12" (305 mm)
32" (815 mm)	48" (1220 mm)	18 to 20" (455 to 510 mm)	32" (815 mm)	14" (355 mm)	24" (610 mm)	13 × 13" (330 × 330 mm)	15" (381 mm)

Figure C

Recommended proportions for conventional masonry fireplaces, based largely on figures given in Ramsey and Sleeper, *Architectural Graphic Standards* (9th ed.), Hoboken, NJ, John Wiley & Sons, 1994.

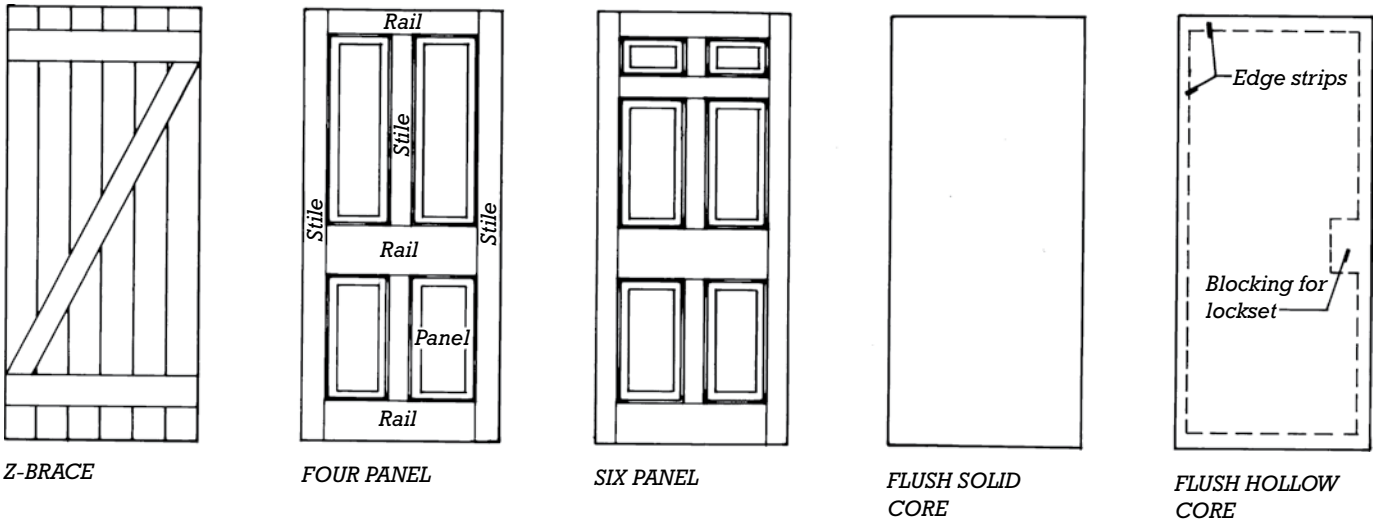


FIGURE 7.23
Types of wood doors.

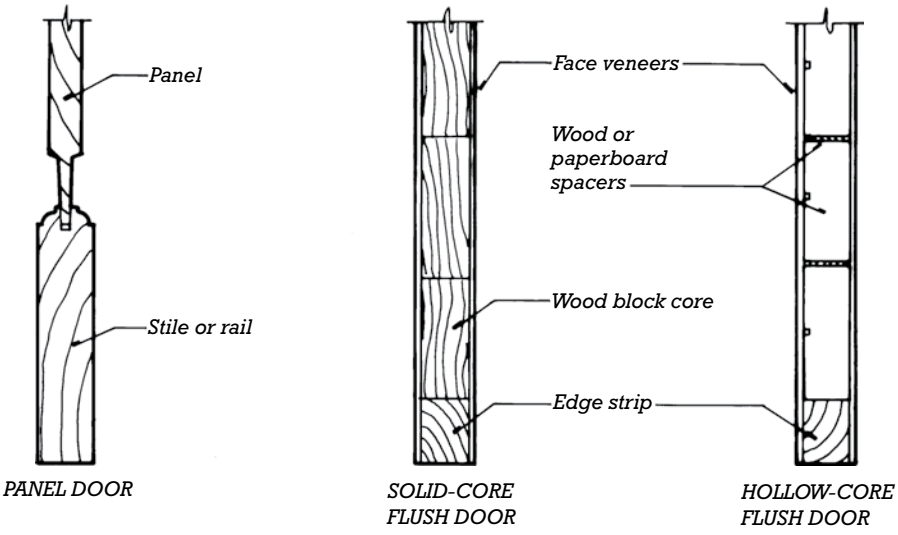


FIGURE 7.24
Edge details of three types of wood doors. The *panel* is loosely fitted to the *stiles* and *rails* in a panel door to allow for moisture expansion of the wood. The spacers and edge strips in hollow-core doors have ventilation holes to equalize air pressures inside and outside the door.

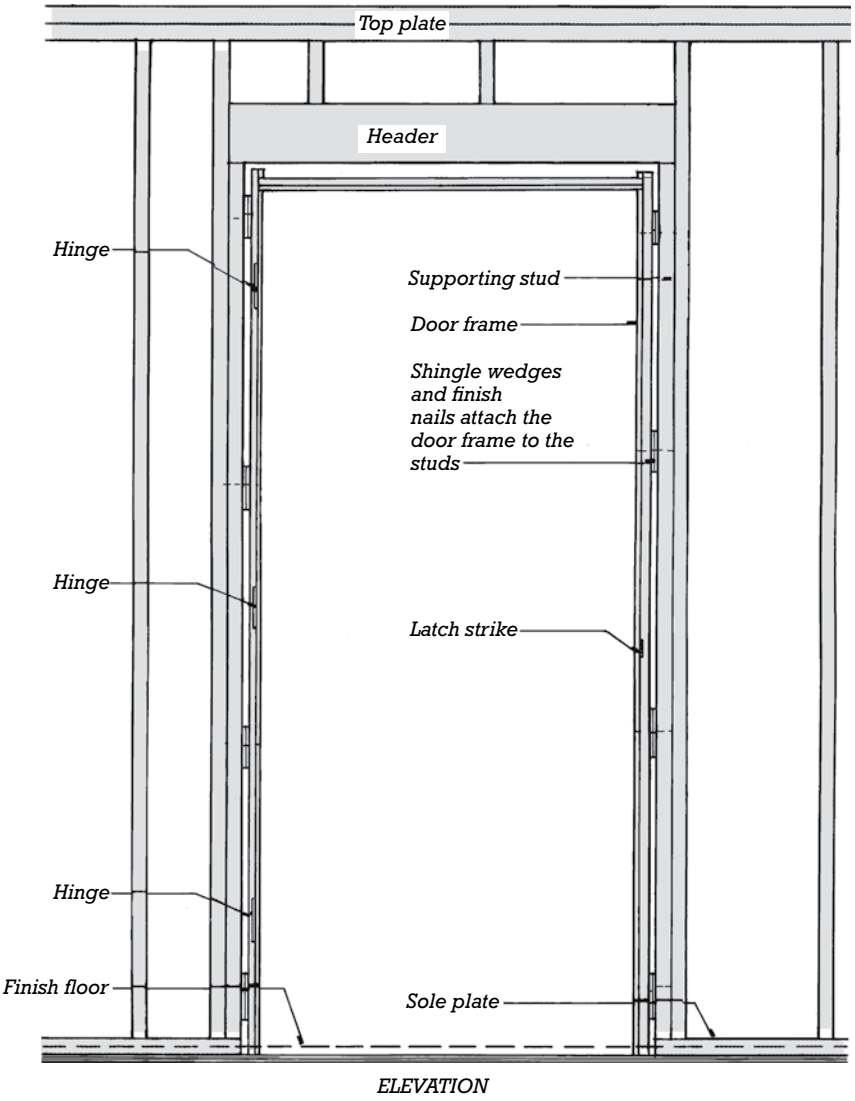


FIGURE 7.25
Installing a door frame in a rough opening. The shingle wedges at each nailing point are paired in opposing directions to create a flat, precisely adjustable shim to support the frame.

Interactive Exercise

is maintained by an interior grid of wood or paperboard spacers to which the veneers are bonded. Flush doors of either type are available in a variety of veneer species, the least expensive of which are intended to be painted.

For speed and economy of installation, most interior doors are furnished *prehung*, meaning that they have been hinged and fitted to frames at the mill. The carpenter on the site merely tilts the prehung door and frame unit up into the rough opening, plumbs it carefully with a spirit level, shims it with pairs of wood shingle wedges between the finish and rough jambs, and nails it to the studs with finish nails through the jambs (Figure 7.25). *Casings* are then nailed around the frame on both sides of the partition to close the ragged gap between the door frame and the wall finish (Figure 7.26). To save the labor of applying casings, door units can also be purchased with *split jambs* that enable the door to be cased at the mill. At the time of installation, each door unit is separated into halves, and the halves are installed from opposite sides of the partition to telescope snugly together before being nailed in place (Figure 7.27).

Window Casings and Baseboards

Windows are cased in much the same manner as doors (Figures 7.28 and 7.29). After the finish flooring is in place, *baseboards* (see Figures 7.36*K*–*N* and 24.31) are installed to cover the gap between the flooring and the wall finish and to protect the wall finish against damage

(a)

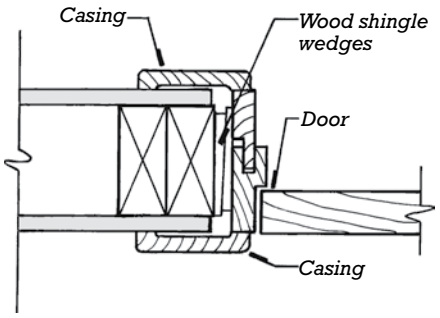
(b)

(c)

(d)

FIGURE 7.26

Casing a door frame. (*a*) The heads of the finish nails in the frame are recessed below the surface of the wood with a steel nail set. (*b*) The top piece of casing, mitered to join the vertical casings, is ready to install, and glue is spread on the edge of the frame. (*c*) The top casing is nailed into place. (*d*) The nails are set below the surface of the wood, ready for filling. *(Photos by Joseph Iano.)*



SECTION THROUGH SPLIT JAMB

FIGURE 7.27

A split-jamb interior door arrives on the construction site prehung and precased. The halves of the frame are separated and installed from opposite sides of the partition.

by feet, furniture legs, and cleaning equipment.

When installing casings or baseboards, the carpenter recesses the heads of finish nails below the surface of the wood, traditionally using a hammer and a *nail set* (a hardened steel punch), or, as is more likely today, a powered finish nail gun. Later, the painters will fill these nail holes with a paste filler and sand the surface smooth after the filler has dried so that the holes will be invisible in the painted woodwork. For transparent wood finishes, nail holes are usually filled after the finishes have been applied, using wax-based fillers that are supplied in a range of colors to match the full range of wood species.

The nails in casings and baseboards must reach through the plaster or gypsum board to penetrate the framing members beneath in order to make a secure attachment. Eight- or ten-penny finish or casing nails are customarily used.

Cabinets

Cabinets for kitchens, bathrooms, bedrooms, workrooms, and other spaces may be either custom- or factory-fabricated. *Custom wood cabinets* are fabricated in specialty woodworking shops according to drawings and specifications prepared individually for each project. Like quality millwork, custom cabinets are constructed to standard grade specifications,

(*a*)

(*b*)

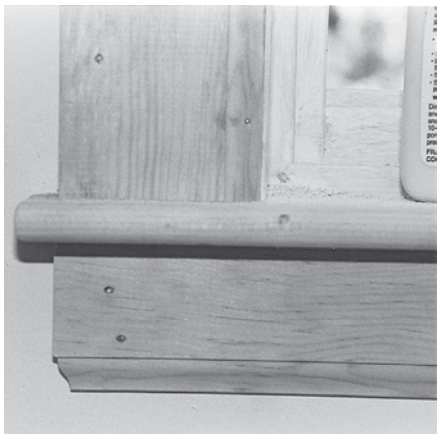
(*c*)

(*d*)

(*e*)

(*f*)

(*g*)



(*h*)

(*i*)

FIGURE 7.28

Casing a window. (*a*) Marking the length of a casing. (*b*) Cutting the casing to length with a power miter saw. (*c*) Nailing the casing. (*d*) Coping the end of a molded edge of an apron with a coping saw so that the molding profile will terminate neatly at the end of the apron. (*e*) Planing the edge of the apron, which has been ripped (sawn lengthwise, parallel to the grain of the wood) from wider casing stock. (*f*) Applying glue to the apron. (*g*) Nailing the apron, which has been wedged temporarily in position with a stick. (*h*) The coped end of the apron, in place. (*i*) The cased window, ready for filling, sanding, and painting. *(Photos by Joseph Iano.)*

FIGURE 7.29
Simple but carefully detailed and skillfully crafted window casings in a restaurant. *(Woo & Williams, Architects. Photographer: Richard Bonarrigo.)*

usually Premium or Custom Grade. Less expensive *manufactured wood cabinets* are factory-manufactured to standard sizes and configurations. Both types of cabinets are usually delivered to the construction site fully finished.

On the construction site, cabinets are installed by shimming against wall and floor surfaces as necessary to make them level and screwing through the backs of the cabinet units into the wall studs (Figures 7.30 and 7.31). The tops are then attached with screws driven up from the cabinets beneath. Kitchen and bath *countertops* are cut out for built-in sinks and lavatories, which are subsequently installed by the plumber.

Finish Stairs

Finish stairs are either constructed in place (Figures 7.32 and 7.33) or shop built (Figures 7.34 and 7.35). Shop built stairs tend to be less expensive to build and easier to install. Constructing stairs on site requires highly skilled carpenters but allows stairs to be built to any configuration and fitted more closely to framing or finish irregularities. Stair treads are usually made of wear-resistant hardwoods, such as oak or maple. Risers and stringers may be made of any reasonably hard wood, such as oak, maple, or Douglas fir.

FIGURE 7.30
Prepainted wood kitchen cabinets installed before the installation of shelves, drawers, doors, and countertops. *(Photo by Edward Allen.)*

FIGURE 7.31
Custom, paneled wood cabinetry contrasts elegantly with contemporary kitchen fixtures and furnishings. The wall behind the cabinets is finished with stone tile, and the floor with solid wood strip flooring. *(Design by Jane Lockhart, courtesy NKBA.)*

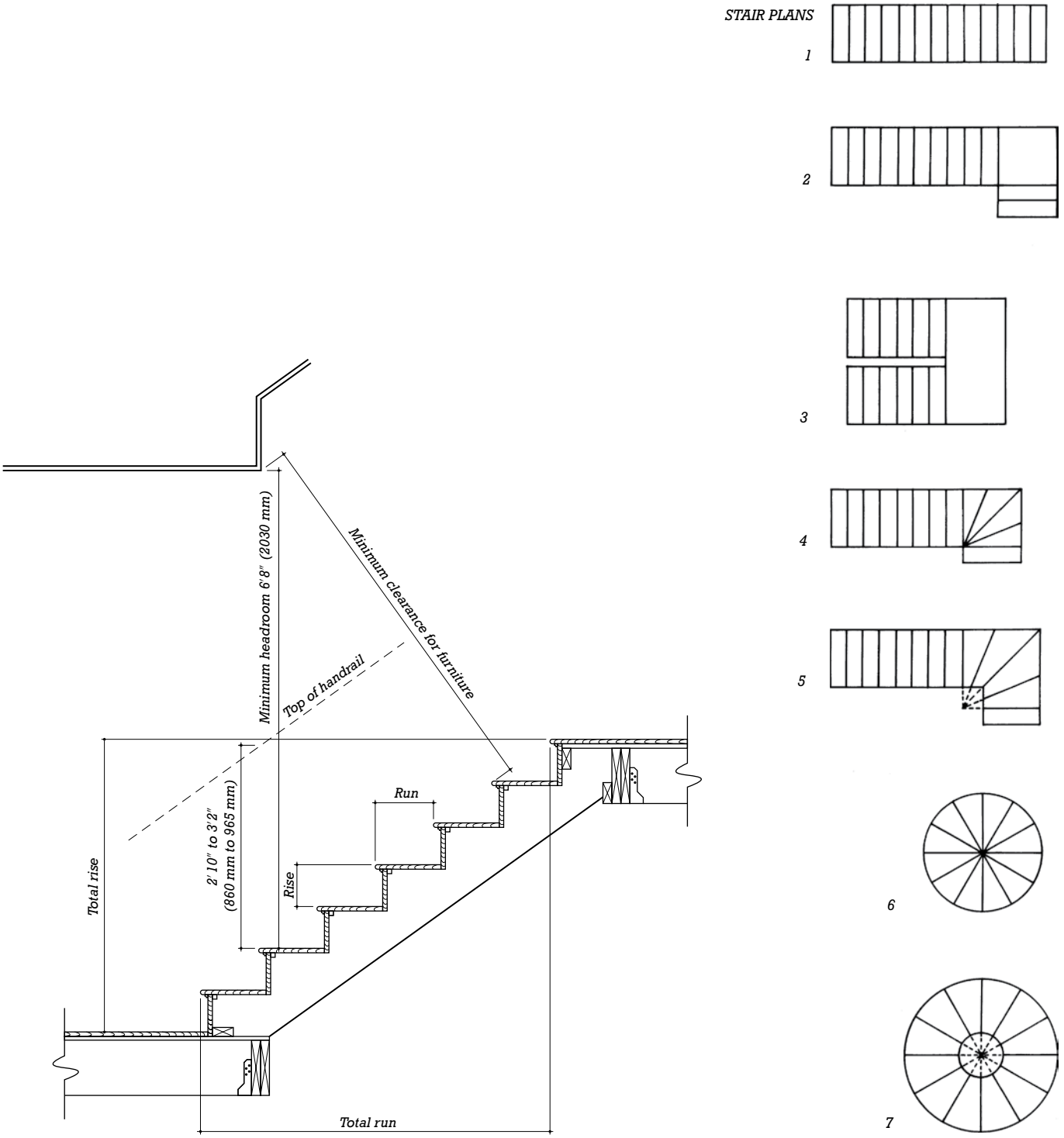


FIGURE 7.32

***Below*: Stair dimensions and clearances for wood frame residential construction. *Right*: Types of stairs. *1.* Straight run. *2.* L-shaped stair with landing. *3.* 180-degree turn with landing. *4.* L-shaped stair with winders (triangular treads). Winders are helpful in compressing a stair into a small space, but are perilously steep where they converge, and their treads become much too shallow for comfort and safety. Building codes limit their minimum dimensions and restrict their use to within dwelling units. *5.* L-shaped stair whose winders have an offset center. The offset center can increase the minimum tread dimension to within legal limits. *6.* A spiral stair (in reality a helix, not a spiral) consists entirely of winders and is generally illegal for any use but a secondary stair in a single-family residence. *7.* A spiral or circular stair with an open center of sufficient diameter can have its treads dimensioned to legal standards.**

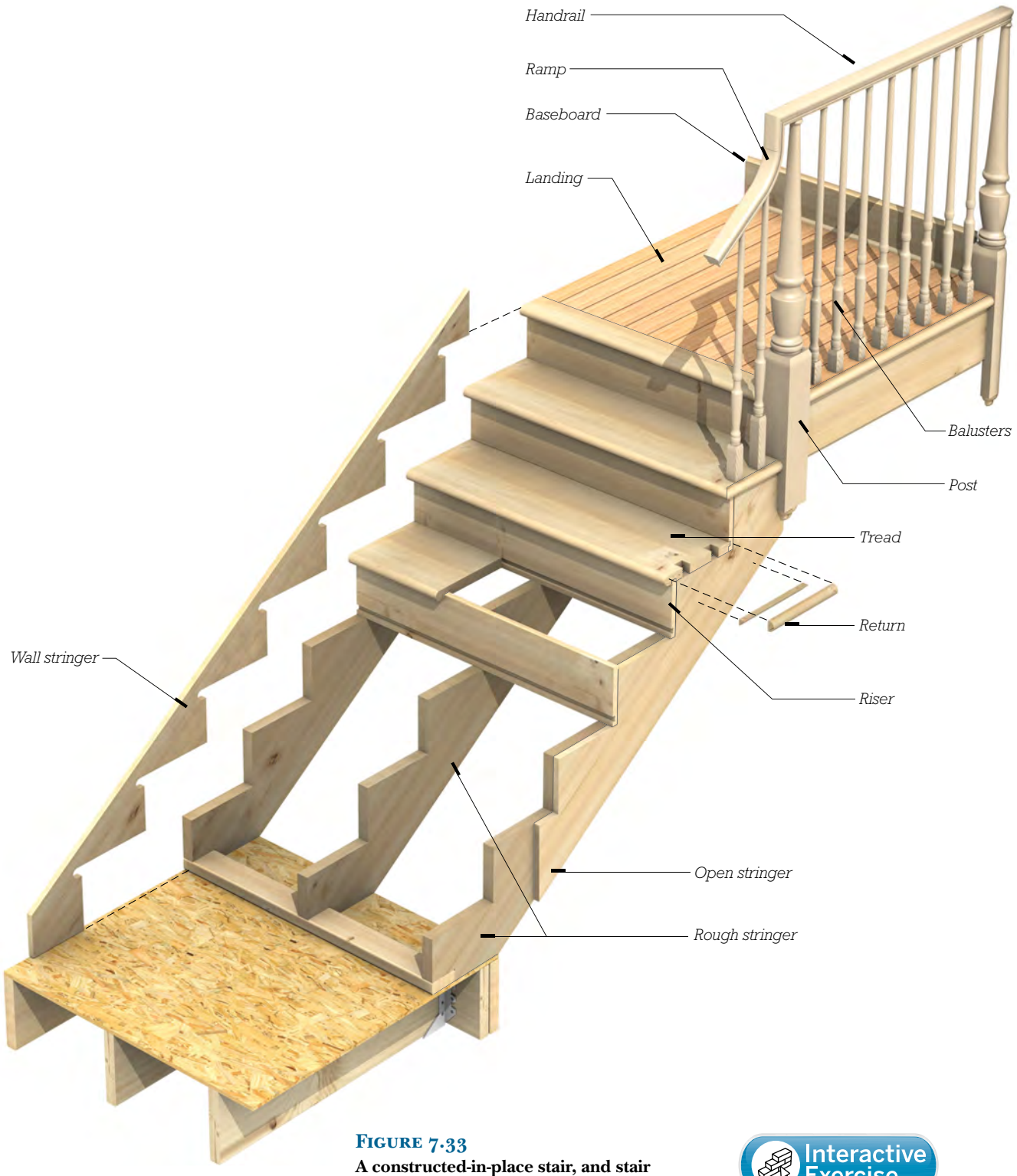


FIGURE 7.33
A constructed-in-place stair, and stair terminology. The joint between the riser and the open stringer is a miter. The balusters, posts, and handrail are purchased ready-made from millwork suppliers and cut to fit.

Interactive Exercise

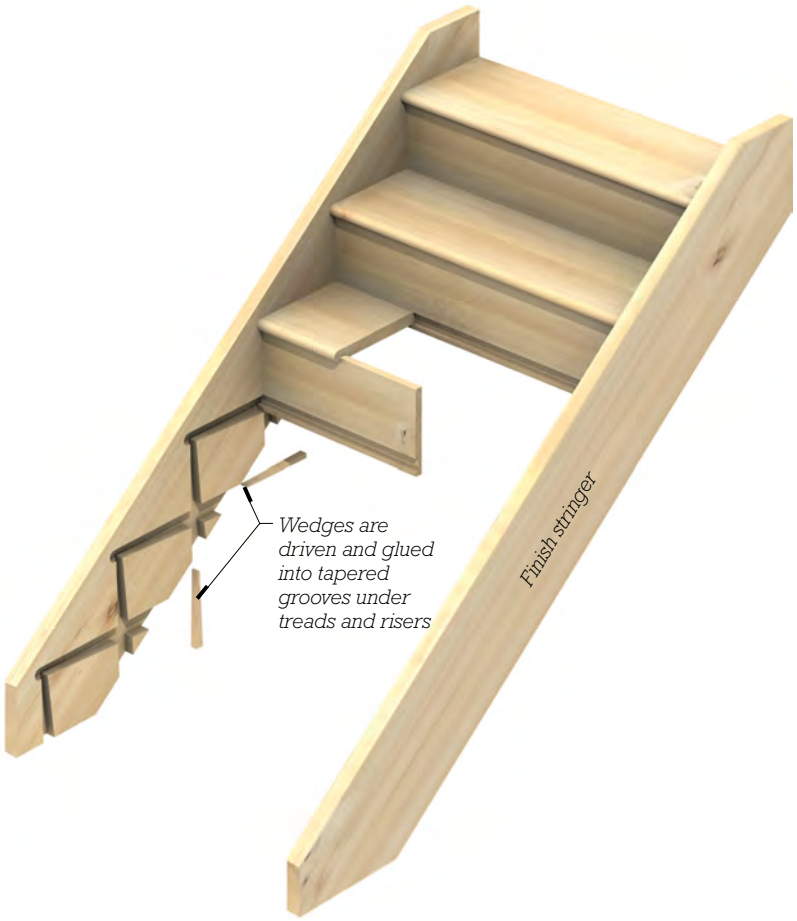


FIGURE 7.34
A shop built stair. All the components are glued firmly together in the shop, and the stair is installed as a single piece.

Three openings are required in stair-cases; the first is the door thro' which one goes up to the staircase, which the less it is hid to them that enter into the house, so much the more it is to be commended. And it would please me much, if it was in a place, where before that one comes to it, the most beautiful part of the house was seen; because it makes the house (even tho' small) seem very large; but however, let it be manifest, and easily found. The second opening is the windows that are necessary to give light to the steps; they ought to be in the middle, and high, that the light may be spread equally every where alike. The third is the opening thro' which one enters into the floor above; this ought to lead us into ample, beautiful, and adorned places.

—Andrea Palladio, *The Four Books of Architecture*, 1570

Miscellaneous Finish Carpentry

Finish carpenters install dozens of miscellaneous items in the average building: closet shelves and poles, pantry shelving, bookshelves, wood paneling, chair rails, picture rails, ceiling moldings, mantelpieces, laundry chutes, folding attic stairs, access hatches, door hardware, weatherstripping, doorstops, and bath accessories (towel bars, paper holders, and so on). Many of these items are available ready-made from millwork and hardware suppliers (Figures 7.36 and 7.37), but others have to be crafted by the carpenter.

(*a*)

(*b*)

FIGURE 7.35
(*a*) A worker completes a highly customized curving stair in a shop. (*b*) Balusters, newel post, and handrail are finely finished in a historical style. *(Courtesy of Staircase & Millwork Co., Alpharetta, GA.)*

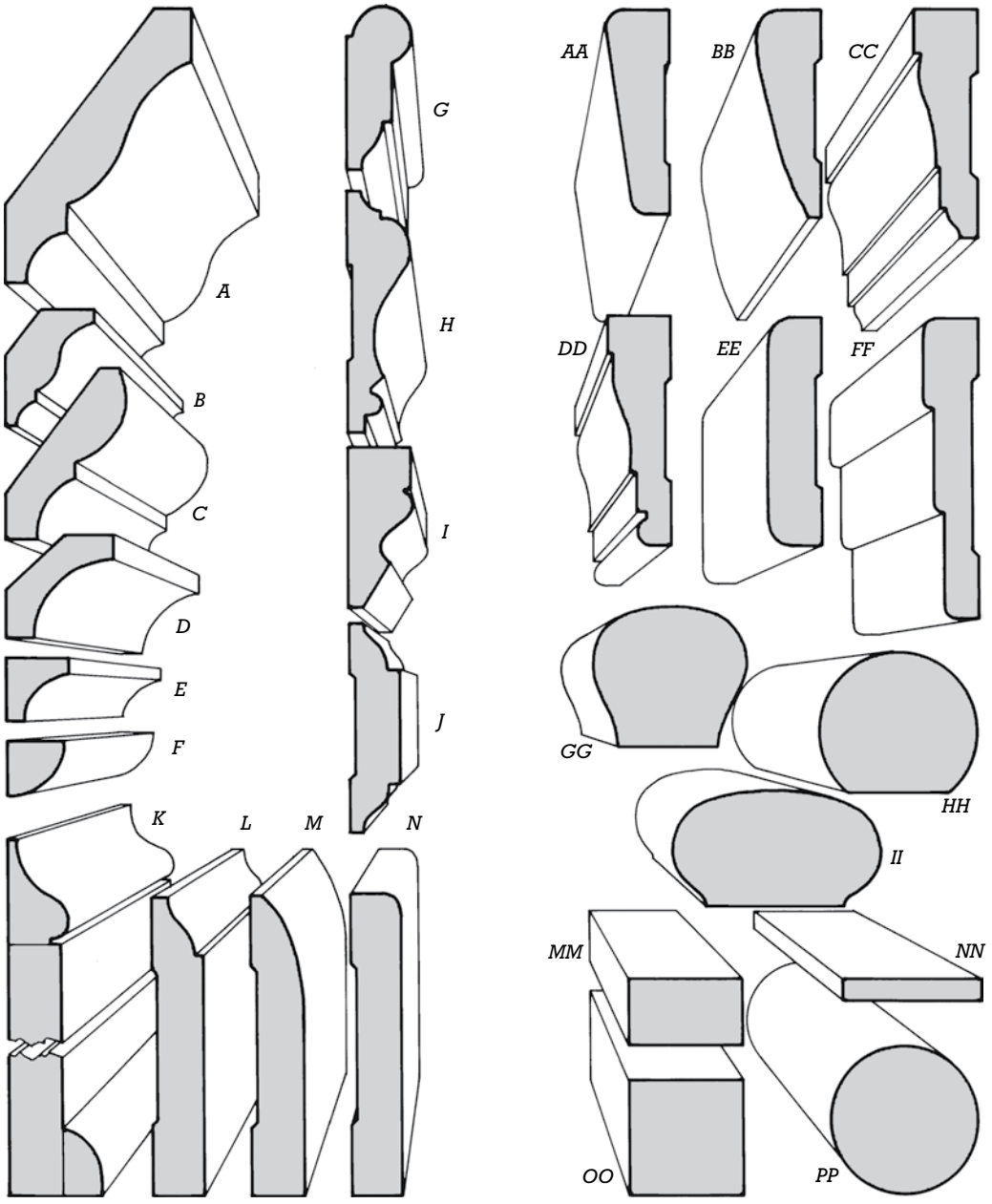


FIGURE 7.36

Some common *molding* patterns for wood interior trim. *A* and *I* are crowns, *C* is a bed, and *D* and *E* are coves. All are used to trim the junction of a ceiling and a wall. *F* is a quarter-round for general-purpose trimming of inside corners. Moldings *G–J* are used on walls. *G* is a picture molding, applied near the top of a wall so that framed pictures can be hung from it at any point on special metal hooks that fit over the rounded portion of the molding. *H* is a chair rail, installed around dining rooms to protect the walls from damage by the backs of chairs. *I* is a panel molding and *J* is a batten, both used in traditional paneled wainscoting. Baseboards (*K–N*) include three single-piece designs and one traditional design (*K*) using a separate cap molding and shoe in addition to a piece of S4S stock that is the baseboard itself (see also Figure 24.31). Notice the shallow groove, also called a "relieved back," in the single-piece baseboards and many other flat moldings on this page. This serves to reduce cupping forces on the piece and makes it easier to install even if it is slightly cupped. Designs *AA–FF* are standard casings for doors and windows. *GG*, *HH*, and *II* are handrail stock. *MM* is representative of a number of sizes of S4S material available to the finish carpenter for miscellaneous uses. *NN* is lattice stock, also used occasionally for flat trim. *OO* is square stock, used primarily for balusters. *PP* represents several available sizes of round stock for balusters, handrails, and closet poles. Wood moldings are furnished in either of two grades: N Grade, for transparent finishes, must be of a single piece. P Grade, for painting, may be finger-jointed or edge-glued from smaller pieces of wood. P Grade is less expensive because it can be made up of short sections of lower-grade lumber with the defects cut out. Once painted, it is indistinguishable from N Grade. The shapes shown here represent a fraction of the moldings that are generally available from stock. Custom molding patterns can be produced easily because the molding cutters used to produce them can be ground quickly to the desired profiles, working from the architect's drawings.

Proportioning Stairs

Building codes ensure the design of safe stairs through a number of dimensional requirements. The limitations for stairs as given in the International Building Code IBC and the International Residential Code IRC are summarized in Figure A. The required width of an exit stairway is also calculated according to the number of occupants served by the stair, in accordance with formulas given in the code, and may be wider than the minimums indicated in this figure. A stair flight may not rise more than 12 feet (3660 mm) between landings. Landings contribute to the safety of a stair by providing a moment's rest for the legs between flights of steps. (Architects also generally avoid designing flights of fewer than three risers because short flights, especially in public buildings, sometimes go unnoticed, leading to dangerous falls.) The width of the landing must equal the width of the stair. The length of a landing must also equal the width of the stair for stairs up to 48 inches (1219 mm) in width, but need not exceed this dimension for wider stairs.

Working within the dimensional limits of the building codes, combinations of tread and riser dimensions that are most comfortable underfoot can be found by using the proportional rule that twice the riser dimension added to the tread dimension should equal 24 to 25 inches (610 to 635 mm). This formula was derived in France two centuries ago from measurements of dimensions of comfortable stairs. Figure B gives an example of how this formula is used in designing a new stair, in this case for a single-family dwelling. Because the IBC does not allow variations that are greater than ⅜ inch (9.5 mm) between successive treads or risers, the floor-to-floor dimension should be divided equally into risers to an accuracy of 0.01 inch or 1 mm to avoid cumulative errors. The framing square used by carpenters in the United States to lay out stair stringers has a scale of hundredths of an inch, and riser dimensions should be given in these units rather than fractions to achieve the necessary accuracy.

Monumental outdoor stairs, such as those that lead to entrances of public buildings, are designed with lower risers and deeper treads than indoor stairs. Many designers relax the proportions of the $2R + T$ formula a bit for outdoor stairs, raising the sum to 26 or 27 inches (660 or 685 mm), but it is best to make a full-scale mockup of a section of such a stair to be sure that it is comfortable underfoot.

	Minimum Width	Maximum Riser Height	Minimum Riser Height	Minimum Tread Depth	Minimum Headroom
Residential stair within the IBC, or any stair subject to the IRC	36" (915 mm)	7¾" (197 mm)	None	10" (254 mm)	6′ 8" (2032 mm)
Nonresidential stair, serving fewer than 50 occupants	36" (915 mm)	7" (178 mm)	4"	11" (279 mm)	6′ 8" (2032 mm)
Nonresidential stair, serving 50 or more occupants	44" (1118 mm)	7" (178 mm)	4"	11" (279 mm)	6′ 8" (2032 mm)

Figure A
Dimensional limitations for stairs as established by the IBC and the IRC.

Procedure	U.S. Customary	Metric
1. Determine the height *(H)* from finish floor to finish floor.	$H = 9'4\frac{3}{8}"$, or 112.375"	$H = 2854$ mm
2. Divide H by the approximate riser height desired—in this example, 7" (180 mm)—and round off to obtain a trial number of risers for the stair.	Approximate riser height = 7" $\frac{H}{7"} = \frac{112.375"}{7"} = 16.05"$ Try 16 risers	Approximate riser height = 180 mm $\frac{H}{180\text{ mm}} = \frac{2854\text{ mm}}{180\text{ mm}} = 15.9$ Try 16 risers
3. Divide H by the trial number of risers to obtain an exact riser height *(R)*. Work to the nearest hundredth of a inch, or the nearest millimeter, to avoid any cumulative error that would result in one riser being substantially lower or higher than the rest. Check to make sure that this riser height falls within the limits set by the building code.	$R = \frac{H}{16} = \frac{112.375"}{16} = 7.02"$ $R = 7.02"$ 7.02" < 7.75" maximum; riser OK	$R = \frac{H}{16} = \frac{2854\text{ mm}}{16} = 178\text{ mm}$ $R = 178$ mm 178 mm < 197 mm maximum; riser OK
4. Substitute this riser height into the formula given for proportioning treads and risers and solve for the tread depth. The depth can be rounded down somewhat if desired, as long as $2R + T > 24$. Check the tread depth against the code minimum.	$2R + T = 25"$ $2(7.02") + T = 25"$ $T = 25" - 14.04"$ T = 10.96", say 10.9" 10.9" > 10" code minimum; tread OK	$2R + T = 635$ mm $2(178\text{ mm}) + T = 635$ mm $T = 635\text{ mm} - 356\text{ mm}$ T = 279 mm, say 275 mm 275 mm > 254 mm code minimum; tread OK
5. Summarize the results of these calculations. There is always one fewer tread than risers in a flight of stairs.	16 risers @ 7.02" 15 treads @ 10.9" Total run = (15)(10.9") = 164.5" = 13′7½"	16 risers @ 178 mm 15 treads @ 275 mm Total run = (15)(275 mm) = 4125 mm = 13′7½"
6. If desired, a steeper or shallower stair can be tried as an alternative by subtracting or adding one tread and one riser, and recalculating dimensions. Reducing the number of treads and risers results in a steeper stair but also shortens the total run of the stair significantly, which is helpful when designing a stair for a limited amount of space. Adding risers and treads results in a stair that is less steep and occupies more space in the plan.	Try 15 risers: $R = \frac{H}{15} = \frac{112.375"}{15} = 7.49"$ 7.49" < 7.75" code minimum; riser OK $2(7.49") + T = 25"$ $T = 10.02"$, say 10.0" 10" = 10" code minimum; tread OK Summary: 15 risers @ 7.49" 14 treads @ 10" Total run = (14)(10") = 11′8" Subtracting one tread and riser shortens the stair by almost 2 feet.	Try 15 risers: $R = \frac{H}{15} = \frac{2854\text{ mm}}{15} = 190\text{ mm}$ 190 mm < 197 mm code minimum; riser OK $2(197\text{ mm}) + T = 635$ mm $T = 255$ mm 255 mm > 254 code minimum; tread OK Summary: 15 risers @ 190 mm 14 treads @ 255 mm Total run = (14)(255 mm) = 3570 mm Subtracting one tread and riser shortens the stair by 555 mm.

FIGURE B

A sample calculation for proportioning a residential stair.

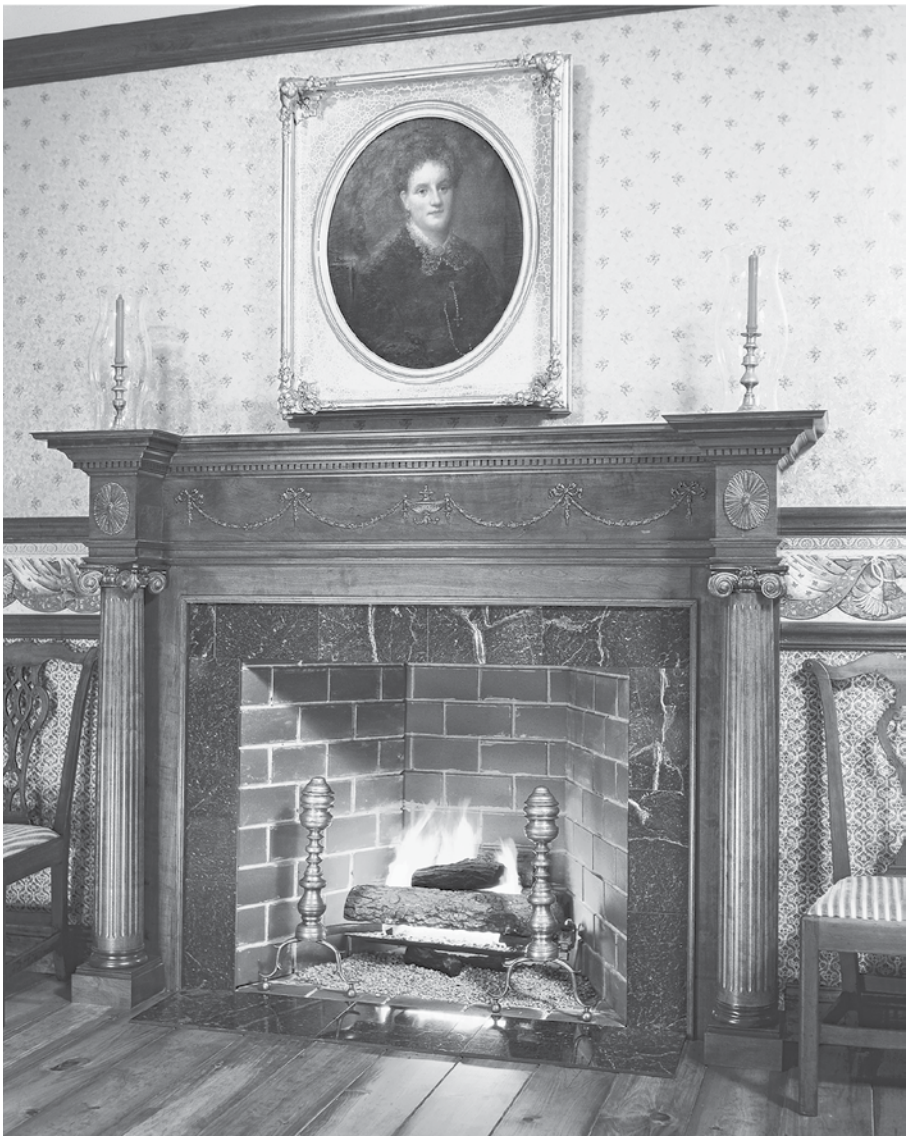


FIGURE 7.37
Fireplace mantels are available from specialized mills in a number of traditional and contemporary designs. Each mantel is furnished largely assembled, but is detailed in such a way that it can easily be adjusted to fit any fireplace within a wide range of sizes. *(Courtesy of Mantels of Yesteryear, P.O. Box 908, 70 West Tennessee Ave., McCaysville, GA 30555;* **www.mantelsofyesteryear.com***; (706) 492-5534, (706) 492-3758 fax.)*

FLOORING AND CERAMIC TILE WORK

Before finish flooring can be installed, the subfloor is scraped free of plaster droppings and swept thoroughly. Clean, undamaged *underlayment panels* of C–C Plugged plywood or particleboard (in areas destined for resilient flooring materials or carpeting) may be glued and nailed over the subfloor, their joints staggered with those in the subfloor to eliminate weak spots. The thicknesses of the underlayment panels are chosen to make the finished floor surfaces as nearly equal in level as possible at junctions between different flooring materials.

In multistory wood light frame commercial and apartment buildings, specially formulated lightweight poured *gypsum* or *portland cement underlayment* is often placed over the subfloor. This has a threefold function: It provides a smooth, level surface for finish floor materials; it furnishes additional fire resistance to the floor construction; and it reduces the transmission of sound through the floor to the apartment or office below. The gypsum or concrete is formulated with superplasticizer additives that make it *self-leveling* as it is applied (Figure 7.38). A minimum thickness is ¾ inch (19 mm). Poured underlayments are also used to level floors in older buildings, to add fire and sound resistance to precast concrete floors, and to embed plastic tubing or electric resistance wires for in-floor radiant heat.

Floor finishing operations require cleanliness and freedom from traffic, so members of other trades are banished from the area as the flooring materials are applied. Hardwood flooring is sanded level and smooth after installation, then vacuumed to remove the sanding

dust. The finish coatings are applied in as dust free an atmosphere as possible to avoid embedded specks. Resilient-flooring installers vacuum the underlayment meticulously so that particles of dirt will not become trapped beneath the thin flooring and cause small bumps in the surface. The finished floors are often covered with heavy sheet or thin board material to protect them during the final few days of construction activity. Carpet installation is less sensitive to dust, and the installed carpets are less prone to damage than hardwood and resilient floorings, but temporary coverings are applied as necessary to protect the carpet from paint spills and water stains.

The application of ceramic tile to a portland cement plaster base coat over metal lath for a shower stall is illustrated in Figure 7.39, and finished ceramic tile work is shown in Figure 7.40. Cementitious backer board may be used as a less costly substitute for a cement plaster base coat. Finished hardwood floors are shown in Figures 7.31 and 7.41. The installation of ceramic tile and finish flooring materials is covered in additional detail in Chapters 23 and 24.

FIGURE 7.38
Workers apply a gypsum underlayment to an office floor. The gypsum is pumped through a hose and distributed with a straightedge tool. Because the gypsum seals against the bottoms of the interior partitions, it can also help reduce sound transmission from one room to another. *(Copyright Gyp-Crete Corporation, Hamel, MN.)*

FIGURE 7.39
Installing sheets of ceramic tile in a shower stall. The base coat of portland cement plaster over metal lath has already been installed. Now the tilesetter applies a thin coat of tile adhesive to the base coat with a trowel and presses a sheet of tiles into it, taking care to align the tiles individually around the edges. A day or two later, after the adhesive has hardened sufficiently, the joints will be grouted to complete the installation. *(Photos by Joseph Iano.)*

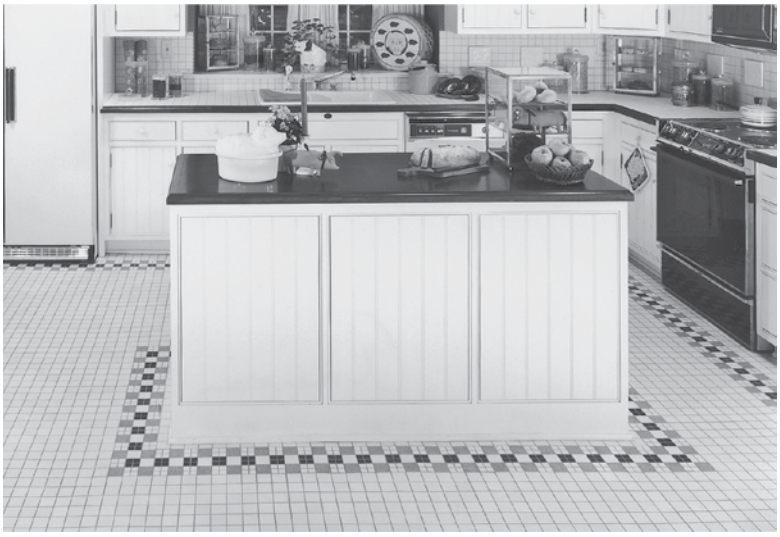


FIGURE 7.40
Ceramic tile is used for the floor, countertops, and backsplash in this kitchen. The border was made by selectively substituting tiles of four different colors for the white tiles used for the field of the floor. *(Designer: Kevin Cordes, courtesy of American Olean Tile.)*

FIGURE 7.41
Varnished oak flooring, millwork, and casework. *(Woo & Williams, Architects. Photographer: Richard Bonarrigo.)*

FINISHING TOUCHES

When flooring and painting are finished, the plumbers install and activate the lavatories, water closets, tubs, sinks, and shower fixtures. Gas lines are connected to appliances, and the main gas valve is opened. The electricians connect the wiring for the heating and air conditioning equipment and (if electric) water heater; mount the receptacles, switches, and lighting fixtures; and put metal or plastic coverplates on the switches and receptacles. The electrical circuits are energized and checked to be sure that they work. The smoke, heat, and carbon monoxide alarms required by most codes in residential structures are also connected

and tested by the electricians, along with any communications, entertainment, and security system wiring. The heating and air conditioning system is completed with the installation of air grills and registers, or with the mounting of metal convector covers, then turned on and tested. Painted surfaces that have been scuffed or marred are touched up, and last-minute problems are identified and corrected through cooperative effort by the contractors, the owner of the building, and the architect. The building inspector is called in for a final inspection and issuance of an occupancy permit. After a thorough cleaning, the building is ready for use.

MasterFormat Sections for Interior Finishes for Light Wood Frame Construction

03 54 00	**CAST UNDERLAYMENT**
04 57 00	**MASONRY FIREPLACES**
06 20 00	**FINISH CARPENTRY**
06 20 23	Interior Finish Carpentry
06 22 00	**MILLWORK**
06 40 00	**ARCHITECTURAL WOODWORK**
06 41 00	**ARCHITECTURAL WOOD CASEWORK**
06 42 00	**WOOD PANELING**
06 43 00	**WOOD STAIRS AND RAILINGS**
06 44 00	**ORNAMENTAL WOODWORK**
06 46 00	**WOOD TRIM**
07 21 00	**THERMAL INSULATION**
07 21 13	Board Insulation
07 21 16	Blanket Insulation
07 21 19	Foamed-In-Place Insulation
07 21 23	Loose-Fill Insulation
07 21 26	Blown Insulation
07 21 29	Sprayed Insulation
07 21 53	Reflective Insulation
07 26 00	**VAPOR RETARDERS**
07 27 00	**AIR BARRIERS**
08 14 00	**WOOD DOORS**
08 14 16	Flush Wood Doors
08 14 33	Stile and Rail Wood Doors
08 71 00	**DOOR HARDWARE**
09 26 00	**VENEER PLASTERING**
09 29 00	**GYPSUM BOARD**
09 30 00	**TILING**
09 64 00	**WOOD FLOORING**
09 68 00	**RESILIENT FLOORING**
09 91 00	**PAINTING**
09 91 23	Interior Painting
09 93 00	**STAINING AND TRANSPARENT FINISHING**
12 32 00	**MANUFACTURED WOOD CASEWORK**
12 26 00	**COUNTERTOPS**

Key Terms

roughing in
DWV (drain–waste–vent) pipe
supply pipe
ductwork
hydronic heating, forced hot water heating
convector
radiant heating
trunk and branch distribution
home run distribution
cross-linked polyethylene (PEX) plastic piping
heating, ventilating, and air conditioning (HVAC)
building enclosure, building envelope
thermal insulation
thermal resistance
R-value, RSI-value
glass fiber batt
thermal bridging
continuous insulation
Passive House standard
superinsulated
radiant barrier
vapor retarder
vapor permeance
vapor barrier
air barrier
airtight drywall approach (ADA)
simple caulk and seal
blower door test
heat recovery ventilator
energy recovery ventilator
three-coat gypsum plaster
wood strip lath
gypsum wallboard, gypsum board, drywall
veneer plaster
millwork
finish carpenter
Economy Grade, Custom Grade, Premium Grade
flue
damper
firebox
smoke shelf
Z-brace door
panel door
flush door
solid-core door
hollow-core door
panel
stile
rail
prehung door
casing
split jamb
baseboard
nail set
custom wood cabinet
manufactured wood cabinet
countertop
handrailramp
landing
baluster
post
tread
return
riser
wall stringer
rough stringer
open stringer
molding
underlayment panel
gypsum cement underlayment
portland cement underlayment
self-leveling

Review Questions

1. List the sequence of operations required to complete the interior of a wood light frame building and explain the logic of the order in which these operations occur.

2. What are some alternative ways of insulating the walls of a wood light frame building to R-values beyond the range normally possible with ordinary 2 × 4 (38 × 89 mm) studs?

3. Why are plaster and gypsum board so popular as interior wall finishes in wood frame buildings? List as many reasons as possible.

4. In general terms, what is the level of humidity in a building at the time finishing operations such as plastering, gypsum board taping, and painting are completed? Why? What should be done about this and why?

5. Summarize the most important things to keep in mind when designing a stair.

6. Describe the function of thermal insulation. When and where is it used?

7. Describe the function of a vapor barrier. When and where is it used?

8. Describe the purpose of an air barrier. When and where is it used?

Exercises

1. Design and detail a fireplace for a building that you are designing, using the information provided in this chapter to work out the exact dimensions and the information in Chapter 8 to help in detailing the masonry.

2. Design and detail a stairway for a building that you are designing. Provide complete dimensions.

3. Visit a wood frame building that you admire. Make a list of the interior finish materials and components, including finishes and species of wood where possible. How does each material and component contribute to the overall feeling of the building? How do they relate to one another?

4. Make measured drawings of millwork details in an older building that you admire. Analyze each detail to discover its logic. What woods were used, and how were they sawn? How were they finished?

Selected References

Architectural Woodwork Institute. *AWI Quality Standards Illustrated*. Reston, VA, updated regularly.

Every detail of every grade of interior woodwork and cabinetry is illustrated and described in this thick volume.

Lstiburek, Joseph. *Builder's Guide to Cold Climates*. Westford, MA, Building Science Corporation, 2006.

This guide, along with companion guides for other major climate zones, explains the roles of insulation, vapor retarders, and air barriers in the performance of the building enclosure, and provides guidelines for the construction of energy-efficient and weather-resistant homes.

Thallon, Rob. *Graphic Guide to Interior Details: For Builders and Designers*. Newtown, CT, Taunton Press, 2004.

Profusely illustrated, clearly written, and encyclopedic in scope, this book offers complete guidance on interior finishing of wood light frame buildings.

Websites

American Olean Tile: www.americanolean.com

Architectural Woodwork Institute: www.awinet.org

Buckley Rumford Company: www.rumford.com

Building Science Corporation: www.buildingscience.com

Decorative Hardwoods Association: www.decorativehardwoods.org

DowDupont (insulation products): www.dow.com/en-us/building

Gypsum Association: www.gypsum.org

Icynene Corporation (spray foam insulation): www.icynene.com

Jeld-Wen Windows & Doors: www.jeld-wen.com/en-us

Owens Corning (insulation products): www.owenscorning.com/insulation

Passive House Institute US: www.phius.org

Tile Council of North America: www.tileusa.com

USG (gypsum products): www.usg.com

Window & Door Manufacturers Association: www.wdma.com

Woodwork Institute: woodworkinstitute.com

8

Brick Masonry

- **History**
- **Mortar**
  - Mortar Ingredients
  - Mortar Mixes
  - Lime Mortar
  - Mortar Hydration
  - Mortar Admixtures

Sustainability and Brick Masonry

- **Brick**
  - Brick Forming
  - Firing Bricks
  - Fly Ash Brick
  - Brick Sizes
  - Brick Classifications
  - Brick Durability, Strength, and Appearance
- **Brick Masonry**
  - Laying Bricks
  - Spanning Openings in Brick Walls
  - Reinforced Brick Masonry
- **Masonry Wall Construction**

Flemish bond brickwork combines simply and directly with cut limestone lintels and sills in this townhouse on Boston's Beacon Hill. *(Photo by James Austin, Cambridge, United Kingdom.)*

Masonry is the simplest of building techniques: The *mason* stacks pieces of material (bricks, stones, or concrete blocks, collectively called *masonry units*) atop one another to make walls. But masonry is also one of the richest and most varied of techniques, with its endless selection of colors, textures, and patterns. And because the pieces of which it is made are small, masonry can take any shape, from a planar wall to a sinuous surface that defies the distinction of roof from wall.

Masonry is the material of earth, taken from the earth and comfortably at home in foundations, pavings, and walls that grow directly from the earth. With modern techniques of reinforcing, however, masonry can rise many stories, and in the form of arches and vaults, masonry can take wing and fly across space.

The most ancient of our building techniques, masonry remains labor intensive, requiring the patient skills of experienced and meticulous artisans to achieve a satisfactory result. It has kept pace with the times and remains highly competitive technically and economically with other systems of structure and enclosure, the more so because one mason can produce in one operation a completely finished, insulated, loadbearing wall ready for use.

Masonry is durable. The designer can select masonry materials that are scarcely affected by water, air, or fire, ones with brilliant colors that will not fade, ones that will stand up to heavy wear and abuse, and make from them a building that will last for generations.

Masonry is a material of the small entrepreneur. One can set out to build a building of bricks with no more tools than a *trowel*, a shovel, a hammer, a measuring rule, a level, a square of scrap plywood, and a piece of string. Yet many masons can work together, aided by mechanized handling of materials, to put up projects as large as the human mind can conceive.

History

Masonry began spontaneously in the creation of low walls by stacking stones or pieces of caked mud taken from dried puddles. Mortar was originally the mud smeared into the joints of the rising wall to lend stability and weathertightness. Where stone lay readily at hand, it was preferred to bricks; where stone was unavailable, bricks were made from local clays and silts. Changes came with the passing millennia: People learned to quarry, cut, and dress stone with increasing precision. Fires built against mud brick walls brought a knowledge of the advantages of burned brick, leading to the invention of the kiln. Masons learned the simple art of turning limestone into lime, and lime mortar gradually replaced mud.

By the 4th millennium BC, the peoples of Mesopotamia were building palaces and temples of stone and sun-dried brick. In the 3rd millennium,

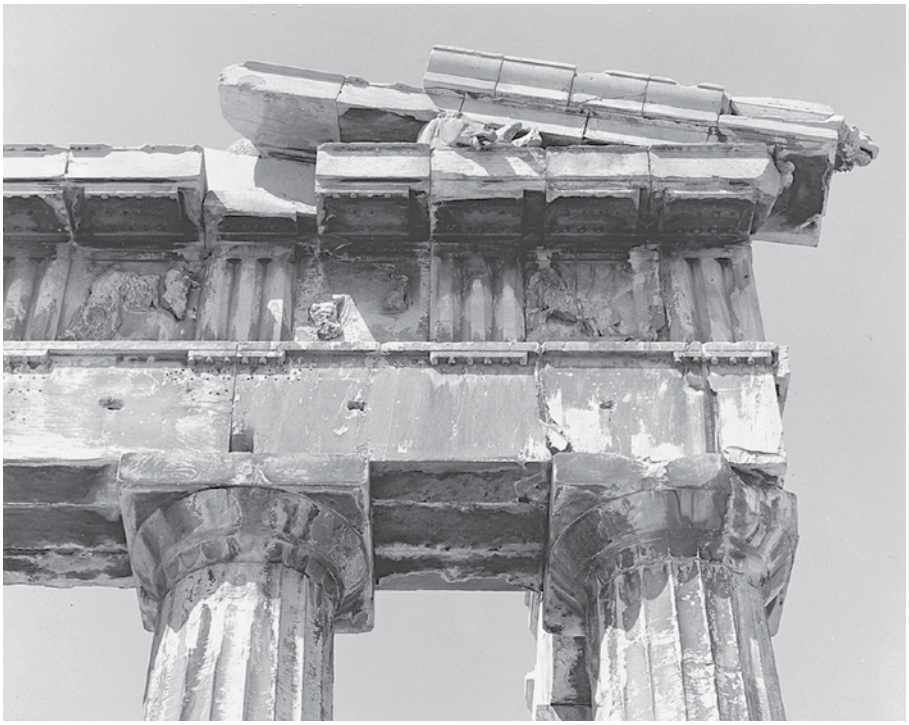


Figure 8.1
The Parthenon, constructed of marble, has stood on the Acropolis in Athens for more than 24 centuries. *(Photo by James Austin, Cambridge, United Kingdom.)*

the Egyptians erected the first of their stone temples and pyramids. In the last centuries prior to the birth of Christ, the Greeks perfected their temples of limestone and marble (Figure 8.1). Control of the Western world then passed to the Romans, who made the first large-scale use of masonry arches and roof vaults in their temples, basilicas, baths, palaces, and aqueducts.

Medieval civilizations in both Europe and the Islamic world brought masonry vaulting to a very high plane of development. The Islamic craftsmen built magnificent palaces, markets, and mosques of brick and often faced them with brightly glazed clay tiles. The Europeans directed their efforts toward fortresses and cathedrals of stone, culminating in the pointed vaults and flying buttresses of the great Gothic churches (Figures 8.2 and 8.3). In Central America, South America, and Asia, other civilizations were carrying on a simultaneous evolution of masonry techniques in cut stone.

During the Industrial Revolution in Europe and North America, machines were developed that quarried and worked stone, molded bricks, and sped the transportation of these heavy materials to the building site. Sophisticated mathematics were applied for the first time to the analysis of the structure of masonry arches and to the art of stonecutting. Portland cement mortar came into widespread use, enabling the construction of masonry buildings of greater strength and durability.

In the late 19th century, masonry began to lose its primacy among the materials of construction. The very tall buildings of the central cities required frames of iron or steel to replace the thick masonry bearing walls that had limited the heights to which one could build. Reinforced concrete, poured rapidly and economically into simple forms made of wood, began to replace brick and stone masonry in foundations and walls. The heavy masonry vault was supplanted by lighter floor and roof structures of steel and concrete that were faster to erect.

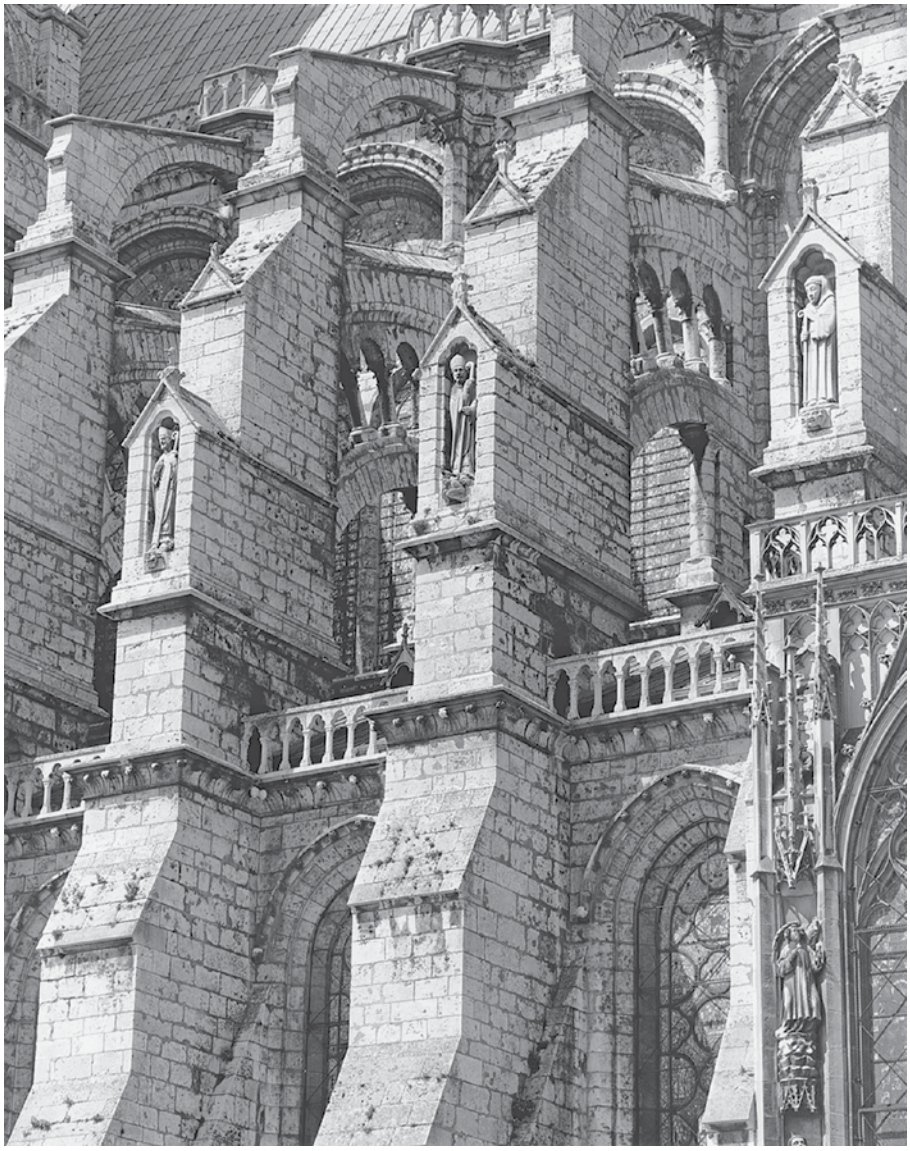


FIGURE 8.2
Construction in ashlar limestone of the magnificent Gothic cathedral at Chartres, France, was begun in AD 1194 and was not finished until several centuries later. Seen here are the flying buttresses that resist the lateral thrusts of the stone roof vaulting. *(Photo by James Austin, Cambridge, United Kingdom.)*

The 19th-century invention of the hollow concrete block helped to avert the extinction of masonry as a craft. The concrete block was much cheaper than cut stone and required much less labor to lay than brick. It could be combined with brick or stone facings to make lower-cost walls that were still satisfactory in appearance. The brick cavity wall, an early 19th-century British invention, also contributed to the survival of masonry, for it produced a warmer, more watertight wall that was later to adapt easily to the introduction of thermal insulation when appropriate insulating materials became available in the mid-20th century.

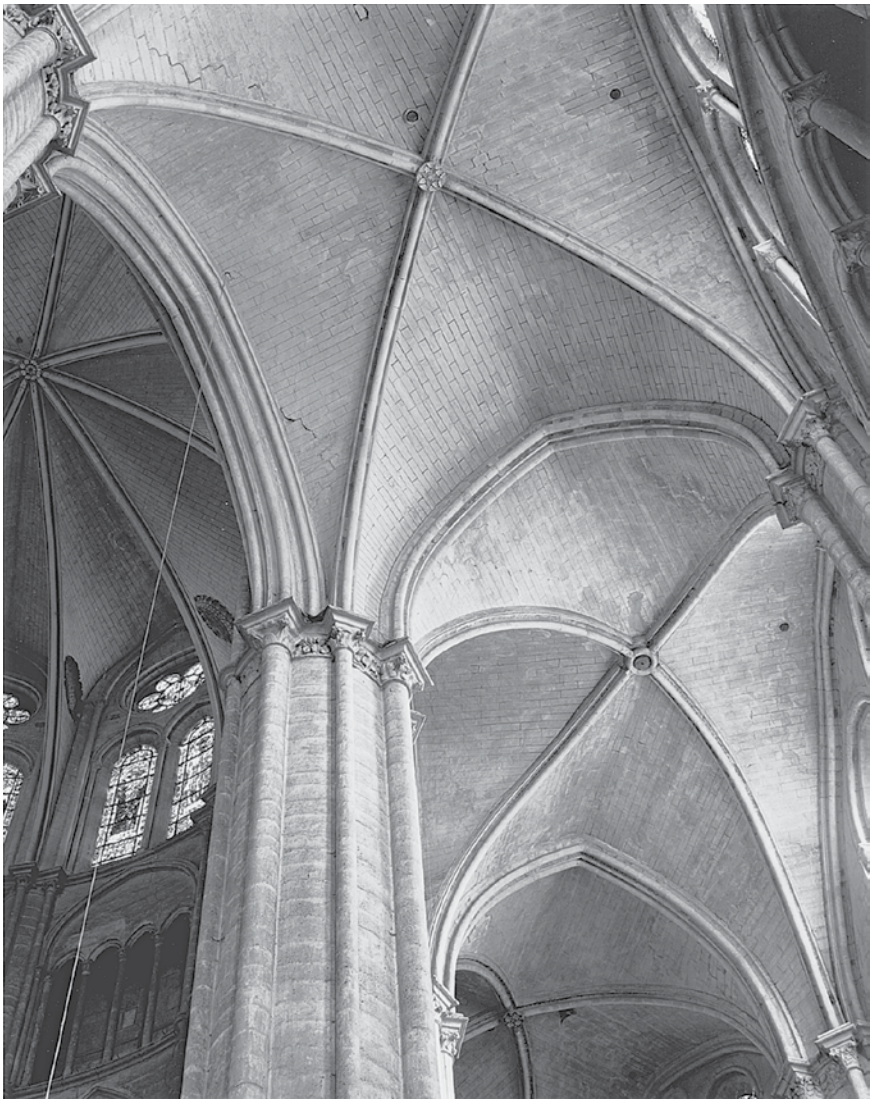


Figure 8.3
The Gothic cathedrals were roofed with lofty vaults of stone blocks. The ambulatory roof at Bourges (built 1195–1275) evidences the skill of the medieval French masons in constructing vaulting to cover even a curving floor plan. *(Photo by James Austin, Cambridge, United Kingdom.)*

Figure 8.4
Despite the steady mechanization of construction operations in general, masonry construction in brick, concrete block, and stone is still based on simple tools and the highly skilled hands that use them. *(Courtesy of International Masonry Institute, Washington, DC.)*

Other 20th-century contributions to masonry construction include the development of techniques for steel-reinforced masonry, high-strength mortars, masonry units (both bricks and concrete blocks) that are higher in structural strength, and masonry units of many types that reduce the amount of labor required for masonry construction (Figure 8.4).

. . . and the smothered incandescence of the kiln: in the fabulous heat, mineral and chemical treasure baking on mere clay, to issue in all the hues of the rainbow, all the shapes of imagination that never yield to time . . . these great ovens would cast a spell upon me as I listened to the subdued roar deep within.

—Frank Lloyd Wright, *In the Nature of Materials*, 1942

If this book had been written as recently as 150 years ago, it would have had to devote little space to construction materials other than masonry and wood. Because the development of other construction materials occurred so late, most of the great works of architecture in the world, and many of the best-developed vernacular architectures, are built of masonry. We live amid a rich heritage of masonry buildings. There is scarcely a town in the world that is without a number of beautiful examples from which the serious student of masonry architecture can learn.

Mortar

Mortar, the material that fills the space between masonry units, is as vital a part of masonry as the masonry units themselves. Mortar cushions the masonry units, giving them full bearing against one another despite their surface irregularities. Mortar seals between the units to keep water and wind from penetrating; it adheres the units to one another to bond them into a monolithic structural unit; and, inevitably, it is important to the appearance of the finished masonry wall.

Mortar Ingredients

The simplest type of mortar is *cement–lime mortar*, made of portland cement, hydrated lime, an inert aggregate, and water. The *portland cement* is the glue-like bonding agent in the mortar. Its composition and manufacture are described in more detail in Chapter 13 of this book. (Only portland cement Types I, II, and III are recommended for use in masonry mortars.) Mortar made only with portland cement, however, is "harsh," meaning that it does not flow well on the trowel or under the brick, so lime is added to impart smoothness and workability. *Lime* is produced by burning limestone or seashells (calcium carbonate) in a kiln to drive off carbon dioxide and leave *quicklime* (calcium oxide). The quicklime is then slaked by adding water that chemically combines with it to form calcium hydroxide, called *slaked lime* or *hydrated lime*. The slaking process, which releases large quantities of heat, is usually carried out in the factory. The hydrated lime is subsequently dried, ground, and bagged for shipment. ASTM specification C207 governs the production of lime. The *aggregate*, sand, must be clean and must be screened to eliminate particles that are too coarse or too fine; ASTM specification C144 establishes standards for mortar sand. Water is also an important ingredient in mortar because it is chemically involved in the curing of the cement and lime. Water used in mortar should be clean and free of acids, alkalis, and organic matter. Water that is potable is generally considered suitable for use in mortar.

Blended hydraulic cements, ASTM C595, are combinations of portland cement with limestone, blast furnace slag, or other cementitious materials, that may be used in place of ordinary portland cement alone in the cement–lime mortar mix.

Masonry cements and mortar cements are prepackaged cements that do not require the addition of lime by the mason on the job site. Their main advantages are convenience, consistency (since they are premixed), and good workability. *Masonry cements* contain various cements, lime, additional plasticizing ingredients, and other additives. Formulations vary from one manufacturer to another, but all must comply with ASTM C91. To achieve a workability equivalent to that of conventional cement–lime mortars, masonry cement mortars are formulated with *air-entraining admixtures* that result in a higher air content in the cured mortar than cement–lime mortar. This reduces the bond strength between the mortar and the masonry unit to about half that of conventional mortar, which means that the flexural and shear strength of the wall is reduced and the wall is more permeable to water. For these reasons, masonry cements are not specified for masonry work that requires high strength and low permeability.

Mortar cements are also blends of portland cement, lime, and other additives. However, they are formulated according to ASTM C1329, with limits on air entrainment that enable them to meet bond strength requirements comparable to those of cement–lime mortars. Structural codes treat mortars made with mortar cement as equivalent to traditional cement–lime mortars.

Cements are available in a range of colors. The most common color is light gray, about the same color as ordinary concrete block. Cements are also available in white, as well as in a range of darker grays, all achieved by controlling the ingredients used

in the manufacture of the cement itself. In the final mortar mix, a much broader range of colors can be produced either by adding pigments to the mortar at the time of mixing or by purchasing dry mortar mix that has been custom colored at the factory. Packaged mortar mixes can be obtained in shades ranging from pure white to pure black, including all the colors of the spectrum.

Because mortar makes up a considerable fraction of the exposed surface area of a brick wall, typically about 20 percent, the color of the mortar is extremely important in the appearance of a brick wall and is almost as important in the appearance of stone or concrete masonry walls. Small sample walls are often constructed before a major building goes under construction to view and compare different color combinations of brick and mortar and make a final selection.

Mortar Mixes

Mortar mixes are specified according to ASTM C270. Four basic *mortar types*, distinguished primarily by differences in strength, are defined:

1. *Type N mortar* is a general-purpose mortar with a balance of good bonding capabilities and good workability. It is recommended for exterior veneers, nonloadbearing exterior walls, parapets, chimneys, and interior loadbearing walls.
2. *Type S mortar* has a higher flexural bond strength than Type N mortar. It is recommended for exterior reinforced masonry, exterior loadbearing masonry walls, and veneers and walls subject to high wind forces or high seismic loads.
3. *Type O mortar* is a low-strength mortar recommended mainly for interior nonloadbearing masonry and historic restoration work.
4. *Type M mortar* is a high-strength mortar with less workability than Type S or N mortars. It is recommended for masonry construction below grade, masonry subject to high lateral or compressive loads, or masonry exposed to severe frost action.

Because lower-strength mortars are more workable than higher-strength mortars, as a general rule, the lowest-strength mortar that meets project requirements is normally chosen. (*Workability* is a general characterization of wet mortar's usability: a workable mortar is smooth and plastic, easy to spread with a trowel, and adheres well to vertical surfaces.) The majority of mortar for masonry work used in new construction is either Type N or Type S. As a memory aid, the letters used to designate mortar types, in order of decreasing strength, come from taking every other letter in the phrase MaSoN wOrK. (Type K mortar is a very-low-strength mortar used in historic preservation work that is no longer part of the ASTM C270 specification.)

According to ASTM C270, mortar mixes may be specified in one of two ways: either by *proportion specification*, in which the quantities of ingredients used to prepare the mix are specified, or by *property specification*, in which the compressive strength and other properties of the hardened mortar—as determined by laboratory testing—are defined. Proportion specification is the simpler (no laboratory testing is required) and more common method. On large jobs, however, property specification gives the mason more flexibility in the choice of mortar ingredients and can result in an overall cost savings, even after the costs of laboratory testing are considered. These two methods are summarized in Figures 8.5 and 8.6, respectively.

Lime Mortar

Modern masonry mortars are made with *hydraulic cements*, that is, cements that cure by chemical reaction with water, a process called "hydration" and discussed in more detail in the next subsection. Until the late 19th and early 20th centuries, however, mortar was made without portland cement, and the lime itself was the bonding agent. Such traditional *lime mortars*, made from a mix of lime, sand, and water, continue to find use principally in the restoration of historic structures. Unlike modern hydraulic cements, lime is a *nonhydraulic cement*, and mortars made with lime as the sole cementing ingredient cure through a reaction with carbon dioxide in the atmosphere. This process, called *carbonation*, occurs gradually and may continue for many years. Such mortars remain at least partially water soluble and retain some ability to self-heal in the event of hairline cracking caused by movement within the wall. By adding other cementitious materials, lime mortars with greater degrees of hydraulic properties can also be formulated.

Mortar Hydration

Hydraulic cement mortars cure by *hydration*, not by drying: In a complex set of chemical reactions, they take up water and combine it with the constituents of the cement and lime to create a dense, strong crystalline structure that binds the sand particles and masonry units together. Once hydraulic cements harden, they become water insoluble.

Mortar that has been mixed but not yet used can become too stiff for use, either by drying out or by commencing its hydration. If the mortar was mixed fewer than 90 minutes prior to its stiffening, it has merely dried and the mason can safely *retemper* it with water to make it workable again. If the unused mortar is more than 2½ hours old, it must be discarded because it has begun to hydrate. On large masonry projects, an *extended-life admixture* is sometimes included in the mortar. This allows the mortar to be mixed

Mortar Type	Parts by Volume of Portland Cement or Blended Hydraulic Cement	Part by Volume of Hydrated Lime	Parts by Volume of Mortar Cement or Masonry Cement	Aggregate, Measured in a Damp, Loose Condition
M	1	¼		Not less than 2 ¼ and not more than 3 times the sum of the volumes of cement and lime materials used.
M	1		1 (Type N)	
M			1 (Type M)	
S	1	Over ¼ to ½		
S	½		1 (Type N)	
S			1 (Type S)	
N	1	Over ½ to 1¼		
N			1 (Type N)	
O	1	Over 1¼ to 2½		
O			1 (Type N)	

Figure 8.5
Mortar types by proportion specification. Generally, the greater the proportion of cement to lime, the greater the compressive strength of the mortar. For each of the four mortar types, the first (shaded row) example is a cement–lime mortar mix consisting of portland cement or blended hydraulic cement, lime, and aggregate. The second and sometimes third examples for each type are mortars made with mortar cement or masonry cement, in which no added lime is required

Mortar Type	Minimum Average Compressive Strength at 28 days
M	2500 psi (17.2 MPa)
S	1800 psi (12.4 MPa)
N	750 psi (5.2 MPa)
O	350 psi (2.4 MPa)

Figure 8.6
Minimum compressive strength for mortar types by property specification. Not shown here, but also included in the ASTM C270 specification, are requirements for maximum air content, minimum water retention (a factor affecting the bond strength of the mortar), and volume ratio of aggregate to cement and lime. When mortar is specified by property, the mason is free to use any mix that meets the specified strength and other requirements as demonstrated through laboratory testing.

in large batches and kept for as long as 72 hours before it must be discarded. When working with highly absorptive brick, the mortar may have to be protected from premature drying that could occur when water is drawn out of the mortar by the bricks. In this circumstance, the bricks are slightly dampened just before laying.

Mortar Admixtures

ASTM C1384 defines other chemical *admixtures* that may be added to mortar to adjust various of its properties. *Set accelerators* help keep freshly mixed mortar from freezing when masonry work takes place in very cold conditions, and *set retarders* help keep mortar from hydrating too quickly in very hot weather. *Integral water repellents* make finished mortar more watertight and reduce *efflorescence* (staining that forms on the surface of a wall when excess moisture carries minerals to the wall surface). Other admixtures may be used to improve workability before setting and bond strength in the finished work.

Sustainability and Brick Masonry

Energy Performance

- The thermal mass properties of brick masonry can help to reduce building energy consumption by lessening peak cooling and heating loads or as a component of passive heating and cooling strategies.

Building and Material Life-Cycle Impacts

- Brick masonry is a durable form of construction that requires relatively little maintenance and can last a very long time.
- When a brick building is demolished, sound bricks may be cleaned of mortar and reused. Brick waste can be crushed and used for landscaping. Brick and mortar waste can also be used as on-site fill. Much such waste, however, is disposed of offsite in landfills.
- In North America, mining, manufacturing, and transporting one Standard clay brick requires approximately 5 MJ (5000 BTU) of energy.
- One European clay brick manufacturer reports the following cradle-to-grave impacts for 1 metric ton of clay brick (approximately 450 bricks), over a 150-year life span:

Nonrenewable primary energy consumption	4200 MJ (3.9 million BTU)
Global warming potential	290 kg (640 lb) CO_2 eq.
Fresh water consumption	380 L (100 gal)

- A North American fly ash (not clay) brick manufacturer EPD reports the following cradle-to-grave impacts for one modular brick and its associated mortar joints, over an 80-year life span:

Nonrenewable primary energy consumption	2.6 MJ (2500 BTU)
Global warming potential	0.13 kg (0.28 lb) CO_2 eq.
Fresh water consumption	46 L (12 gal)

Material and Production Attributes

- Brick manufacturing produces few waste materials. Unfired clay is easily recycled into the production process. Fired bricks that are unusable are ground up and recycled into the production process or used as landscaping material.
- Brick manufacturing plants are usually located close to the sources of their raw materials.
- Fly ash brick has a high recycled-materials content and contributes to the diversion of this waste material from landfills or storage ponds. However, the possible long-term impacts of introducing this hazardous material into the building-materials product stream continues to be a point of some disagreement.
- Most bricks are sold for use in regional markets close to their point of manufacture. This reduces the energy required for shipping and makes much brick eligible for credit as a regional material.

Unhealthful Materials and Emissions

- Brick masonry is not normally associated with indoor air quality problems.
- Brick masonry is resistant to moisture damage and mold growth.
- Construction with brick masonry can reduce reliance on paint finishes, a source of volatile organic compounds.

Responsible Industry Practices and Social Impacts

- Clay and shale, the raw materials for bricks, are plentiful. They are usually obtained from open pits, with the attendant disruption of drainage, vegetation, and wildlife habitat.
- Since approximately 1970, U.S. brick manufacturers have implemented manufacturing efficiencies that have reduced the energy required to produce bricks by a factor of greater than three.
- Industry efforts have also led to reductions in emissions of kiln exhaust air pollutants, lime waste, dust, vehicular emissions during transport of brick, and oil and antifreeze wastes.

Brick

Among the masonry materials, brick is special in two respects: fire resistance and size. As a product of fire, it is the most resistant to building fires of any masonry unit type. Its size may account for much of the love that many people instinctively feel for brick: A traditional brick is shaped and dimensioned to fit the human hand. Hand-sized bricks are less likely to crack during drying or firing than larger bricks, and they are easy for the mason to manipulate. This small unit size makes brickwork flexible in adapting to small-scale geometries and patterns and gives a pleasing scale and texture to a brick wall or floor.

Brick Forming

Because of their weight and bulk, which make them expensive to ship over long distances, *bricks* are produced by a large number of relatively small, widely dispersed factories from a variety of local clays and shales. The raw material is dug from pits, crushed, ground, and screened to reduce it to a fine consistency. It is then tempered with water to produce a plastic clay ready for forming into bricks.

Three major methods are used today for forming bricks: the soft mud process, the dry-press process, and the stiff mud process. The oldest is the *soft mud process*, in which a relatively moist clay (20 to 30 percent water) is pressed into simple rectangular molds, either by hand or with the aid of molding machines (Figure 8.7). To keep the sticky clay from adhering to the molds, the molds may be dipped in water immediately before being filled, producing bricks with a relatively smooth, dense surface that are known as *water-struck bricks*. If the wet mold is dusted with sand just before forming the brick, *sand-struck* or *sand-mold bricks* are produced, with a matte-textured surface.

The *dry-press process* is used for clays that shrink excessively during drying. Clay mixed with a minimum of water (up to 10 percent) is pressed into steel molds by a machine working at a very high pressure.

The high-production *stiff mud process* is the least costly and most widely used today. Clay containing 12 to 15 percent water is passed through a vacuum to remove any pockets of air, then extruded through a rectangular die (Figures 8.8 and 8.9). As the clay leaves the die, textures or thin mixtures of colored clays may be applied to its surface as desired. The rectangular column of moist clay is pushed by the pressure of extrusion across a cutting table, where automatic cutter wires slice it into bricks.

Bricks produced by the stiff mud process are highly uniform in dimension and shape. Where more

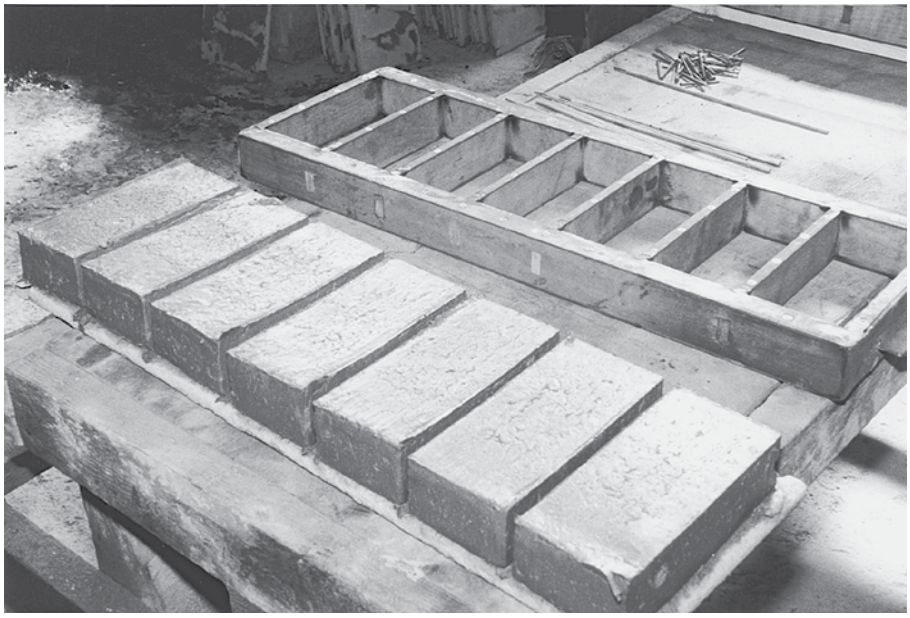


FIGURE 8.7
A simple wooden mold produces seven water-struck bricks at a time. *(Photo by Edward Allen.)*

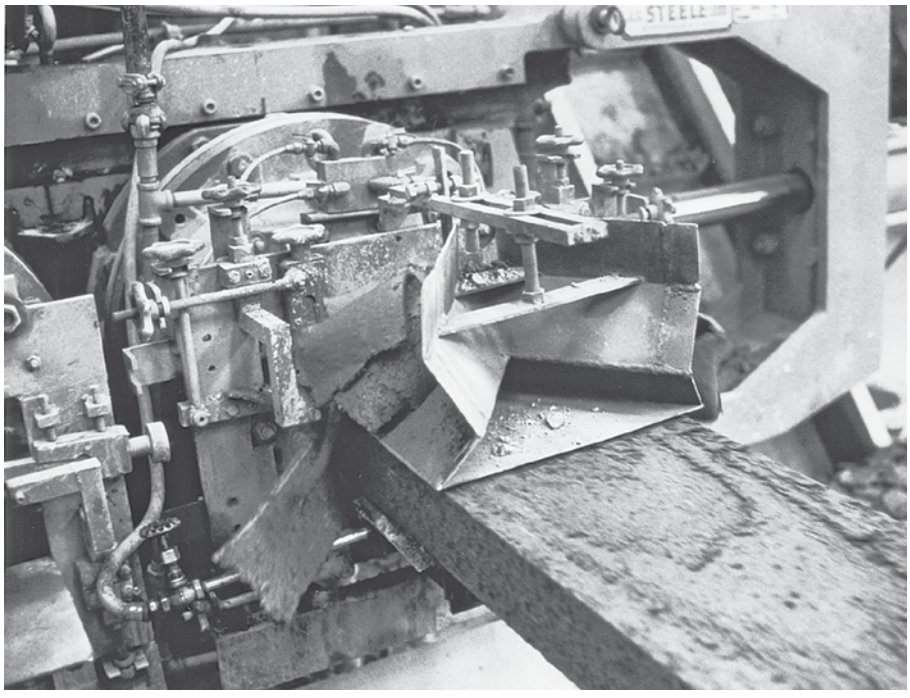


FIGURE 8.8
A column of clay emerges from the die in the stiff mud process of molding bricks. *(Courtesy of Brick Institute of America.)*

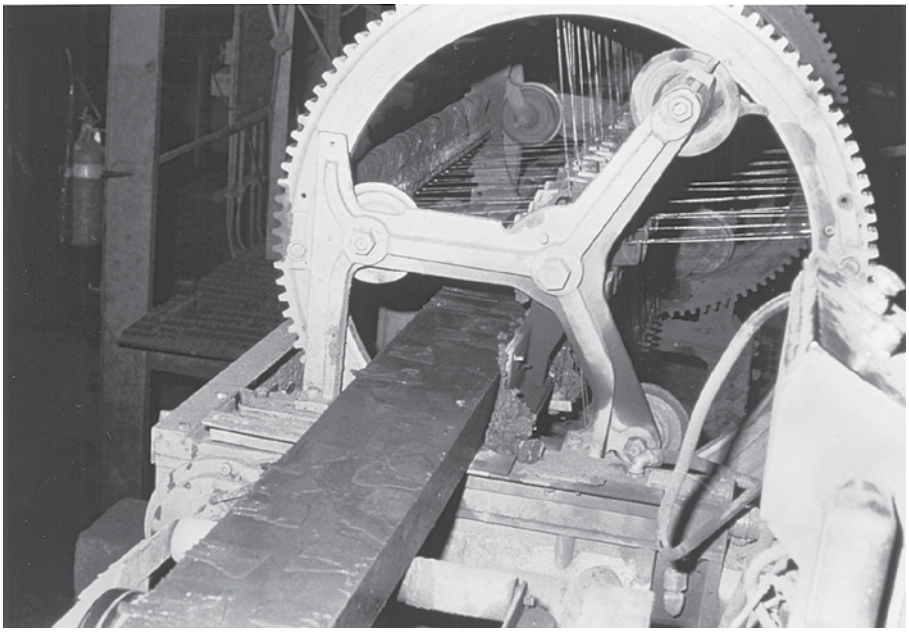


FIGURE 8.9
Rotating groups of parallel wires cut the column of clay into individual bricks, ready for drying and firing. *(Courtesy of Brick Institute of America.)*

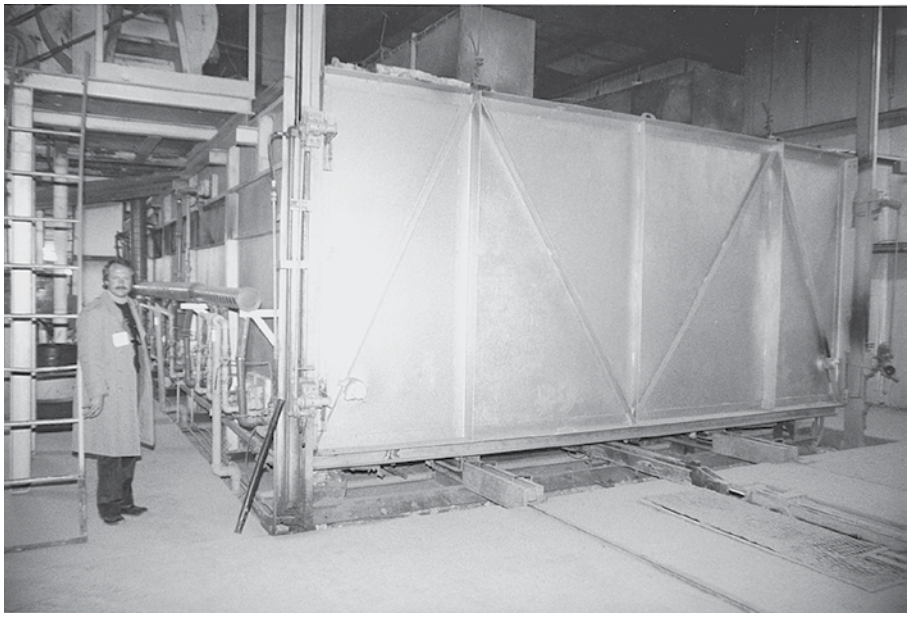
variation in appearance among units is desired, the bricks can be *tumbled* prior to firing. Tumbling softens edges and corners, and introduces a greater individuality in appearance among units.

After molding by any of these three processes, the bricks are dried for one or two days in a low-temperature dryer kiln. They are then ready for transformation into their final form by a process known as *firing* or *burning*.

Firing Bricks

Before the advent of modern kilns, bricks were most often fired by stacking them in a loose array called a *clamp*, covering the clamp with earth or clay, building a wood fire under the clamp, and maintaining the fire for a period of several days. After cooling, the clamp was disassembled and the bricks were sorted according to the degree of burning each had experienced. Bricks closest to the fire (*clinker bricks*) were often overburned and distorted, making them unattractive and therefore unsuitable for use in exposed brickwork. Bricks in a zone of the clamp near the fire were fully burned but undistorted, suitable for exterior-facing bricks with a high degree of resistance to weather. Bricks farther from the fire were softer and were set aside for use as backup bricks, while some bricks from around the perimeter of the clamp were not burned sufficiently for any purpose and were discarded. In the days before mechanized transportation, bricks for a building were often produced from clay obtained from the building site and were burned in clamps adjacent to the work.

(*a*)



(*b*)

(*c*)

FIGURE 8.10

Three stages in the firing of water-struck bricks. (*a*) Bricks stacked on a kiln car ready for firing. The open passages between the bricks allow the hot kiln gases to penetrate to the interior of the stack. The bed of the kiln car is made of a refractory material that is unaffected by the heat of the kiln. The rails on which the car runs are recessed in the floor. (*b*) The cars of bricks are rolled into the far end of this gas-fired periodic kiln. When firing has been completed, the large door in the near end of the kiln is opened and the cars of bricks are rolled out on the rails that can be seen at the lower right of the picture. (*c*) After the fired bricks have been sorted, they are strapped into "cubes" for shipping. *(Photo by Edward Allen.)*

Today, bricks are usually burned in either a periodic kiln or a continuous tunnel kiln. The *periodic kiln* is a fixed structure that is loaded with bricks, fired, cooled, and unloaded (Figure 8.10). For higher productivity, bricks are passed continuously through a long *tunnel kiln* on special railcars to emerge at the far end fully burned. In either type of kiln, the first stages of burning are *water smoking* and *dehydration*, which drive off the remaining water from the clay. The next stages are *oxidation* and *vitrification*, during which the temperature rises to 1800 to 2400 degrees Fahrenheit (1000 to 1300°C) and the clay is transformed into a ceramic material. This may be followed by a stage called *flashing*, in which the fire is regulated to create a reducing atmosphere in the kiln that develops color variations in the bricks. Finally, the bricks are cooled under controlled conditions to achieve the desired color and avoid thermal cracking. The cooled bricks are inspected, sorted, and packaged for shipment. The entire process of firing takes 40 to 150 hours and is monitored continuously to maintain product quality. Considerable shrinkage takes place in the bricks during drying and firing; this must be taken into account when designing the molds for the bricks. The higher the temperature is, the greater the shrinkage and the darker the color of the brick. Bricks are often used in a mixed range of colors, with the darker bricks inevitably being smaller than the lighter bricks. Even in bricks of uniform color, some size variation is to be expected, and bricks, in general, are subject to a certain amount of distortion from the firing process.

The color of a brick depends on the chemical composition of the clay or shale and the temperature and chemistry of the fire in the kiln. Higher temperatures, as noted in the previous paragraph, produce darker bricks. The iron that is prevalent in most clays turns red in an oxidizing fire and purple in a reducing fire.

Other chemical elements interact in a similar way to the kiln atmosphere to make still other colors. For bright colors, the faces of the bricks can be glazed like pottery, either during the normal firing or in an additional firing.

Fly Ash Brick

Fly ash bricks are made from fly ash (a waste product from coal-fired power generation), sand, and water. The fly ash acts as the binder and the sand as the aggregate. These two ingredients are mixed with water and smaller amounts of other ingredients, compacted into molds, and steam cured. The resulting masonry units are equal in performance and similar in appearance to traditional clay bricks.

In comparison to the tradition kiln brick firing process, steam curing of fly ash bricks requires significantly less energy. As a result, the environmental impacts of fly ash bricks can be significantly less than that of clay.

Brick Sizes

There is no truly standard brick. The nearest thing in the United States is the *modular brick*, dimensioned to construct walls in modules of 4 inches (101 mm) horizontally and 8 inches (203 mm) vertically. More broadly, the term *modular* can be applied to any brick that is sized, such that when the thickness of mortar joints is included, dimensioning of the wall conforms to convenient whole units such as 4, 6, 8, 12, or 16 inches (102, 152, 203, 305, or 406 mm). The sizing of *nonmodular* bricks, particularly in width or length, does not necessarily conform to convenient whole number dimensions in the constructed wall.

Figure 8.11 describes sizes for just a handful of the great many bricks available. In practice, the designer, when selecting bricks for a building, usually views locally available samples before completing the drawings for the building and dimensions the drawings in accordance with the size of the bricks selected. (Dimensioning of brick masonry is discussed further later in this chapter.)

The use of larger bricks can lead to substantial economies in construction. For example, only two *Utility* bricks, nominally 4 inches × 12 inches in height and length, are required to complete an 8-inch high × 12-inch long area of wall. In comparison, it requires four and one-half modular bricks to complete the same area. Because fewer Utility bricks are required, labor costs to construct the wall are lower, and because of the smaller proportion of mortar, the compressive strength of the wall is higher. The designer should also consider, of course, that a wall built with larger bricks changes the viewer's perception of the scale of the wall.

Custom shapes and sizes of brick are often required for buildings with special details, ornamentation, or unusual geometries (Figures 8.12 and 8.13). These are readily produced by most brick manufacturers if sufficient lead time is given.

	Actual Dimensions			Nominal Dimensions			
	W	H	L	W	H	L	Vertical Coursing
Modular	3⅝ (*92*) 3½ (*89*)	2¼ (*57*)	7⅝ (*194*) 7½ (*191*)	4 (*102*)	2⅔ (*68*)	8 (*203*)	3C = 8 (*203*)
Engineer Modular	3⅝ (*92*) 3½ (*89*)	2 13/16 (*71*) 2¾ (*70*)	7⅝ (*194*) 7½ (*191*)	4 (*102*)	3⅕ (*81*)	8 (*203*)	5C = 16 (*406*)
Closure Modular	3⅝ (*92*) 3½ (*89*)	3⅝ (*92*) 3½ (*89*)	7⅝ (*194*) 7½ (*191*)	4 (*102*)	4 (*102*)	8 (*203*)	1C = 4 (*102*)
Roman	3⅝ (*92*) 3½ (*89*)	1⅝ (*41*) 1½ (*38*)	11⅝ (*295*) 11½ (*292*)	4 (*102*)	2 (*51*)	12 (*305*)	2C = 4 (*102*)
Norman	3⅝ (*92*) 3½ (*89*)	2¼ (*57*)	11⅝ (*295*) 11½ (*292*)	4 (*102*)	2⅔ (*68*)	12 (*305*)	3C = 8 (*203*)
Utility	3⅝ (*92*) 3½ (*89*)	3⅝ (*92*) 3½ (*89*)	11⅝ (*295*) 11½ (*292*)	4 (*102*)	4 (*102*)	12 (*305*)	1C = 4 (*102*)
Meridian	3⅝ (*92*) 3½ (*89*)	3⅝ (*92*) 3½ (*89*)	15⅝ (*397*) 15½ (*394*)	4 (*102*)	4 (*102*)	16 (*406*)	1C = 4 (*102*)
Standard	3⅝ (*92*) 3½ (*89*)	2¼ (*57*)	8 (*203*)				3C = 8 (*203*)
Queen	2¾ (*70*) 3 (*76*)	2¾ (*70*)	7⅝ (*194*) 8 (*203*)				5C = 16 (*406*)
King	2¾ (*70*) 3 (*76*)	2⅝ (*67*) 2¾ (*70*)	9⅝ (*244*) 9¾ (*248*)				5C = 16 (*406*)

FIGURE 8.11

Examples of brick types and sizes. Dimensions are given first in inches and then in (mm). For modular bricks, shown in the shaded rows, both actual dimensions and nominal dimensions (the size of the brick plus one mortar joint) are provided. For nonmodular brick, only actual dimensions are given. Standard mortar joint widths vary from ⅜ to ½ inch (9.5 to 12.7 mm). Where two dimensions are provided within one table entry, size may vary within that range.

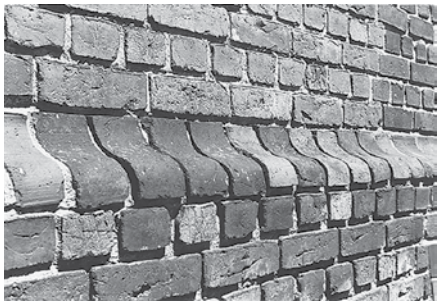
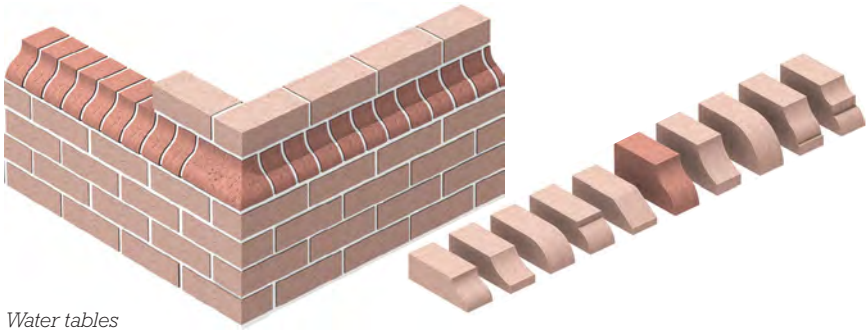
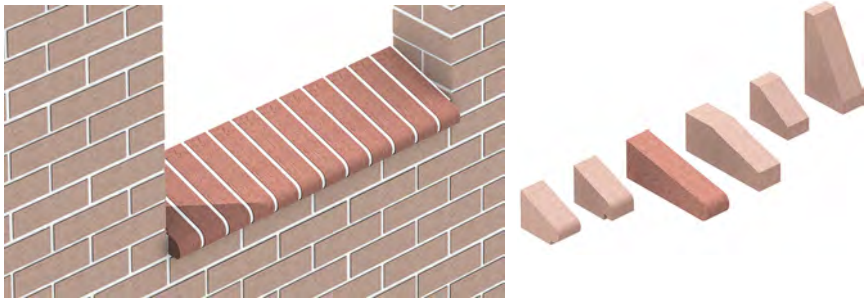


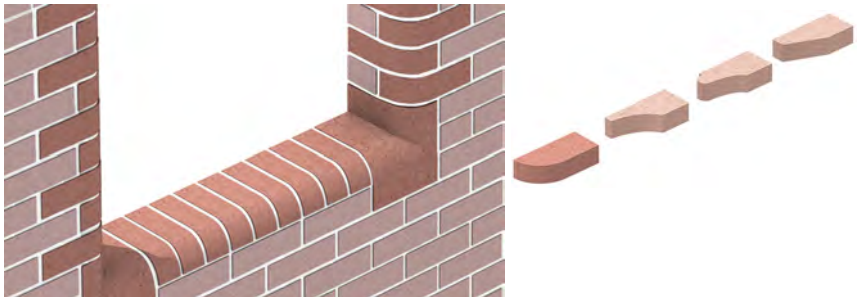
FIGURE 8.12
Bricks may be custom molded to perform particular functions. This rowlock water table course in an English bond wall was molded to an ogee curve. *(Photo by Edward Allen.)*



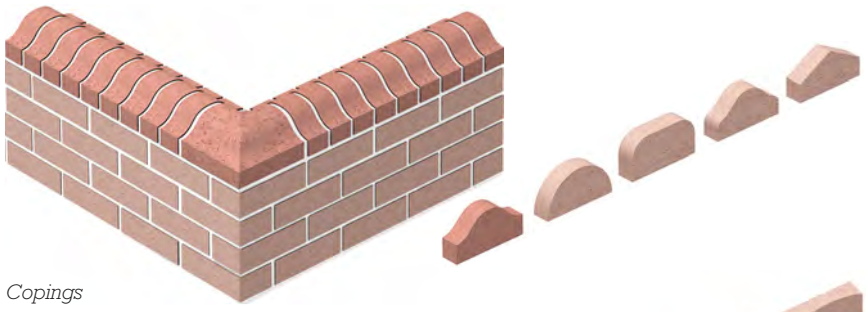
Water tables



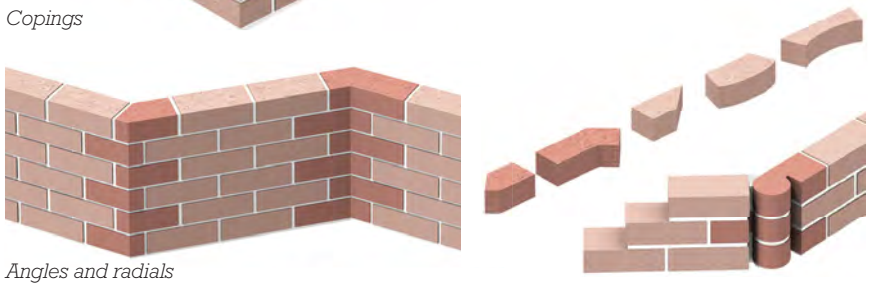
Sills



Jambs



Copings



Angles and radials

FIGURE 8.13
Some commonly used custom brick shapes. Notice that each water table, jamb, and coping brick shape requires special inside and outside corner bricks as well as the basic rowlock or header brick. The angle bricks are needed to make neat corners in walls that meet at other than right angles. The hinge brick at the extreme lower right of the drawing is a traditional shape that can be used to make a corner at any desired angle. Radial bricks produce a smoothly curved wall surface of any specified radius. Common shapes not pictured here include voussoirs for any desired shape and size of arch and rounded-edge bricks for stair treads.

Brick Classifications

The bricks most commonly used in building construction are classified as facing brick (ASTM C216), building brick (ASTM C62), and hollow brick (ASTM C652). *Facing bricks* (also called *face brick*) are intended for both structural and nonstructural uses where appearance is important. *Building bricks* are used where appearance does not matter, such as in parts of a masonry wall concealed behind face bricks in the finished work. Both facing bricks and building bricks are specified as *solid units*. Solid units may, in fact, be genuinely solid, or despite their name, they may be *cored* or *frogged* (Figure 8.14), as long as any plane measured parallel to the bearing surface of the brick is at least 75 percent solid. By reducing the volume and thickness of the clay, cores and frogs permit more even drying and firing of bricks, reduce fuel costs for firing, reduce shipping costs, and create bricks that are lighter and easier to handle. *Hollow bricks* may be up to 60 percent void. Their lighter weight in comparison to solid bricks can result in lower construction costs and reduced loads on the building structure. The larger voids within the units also enable the insertion and grouting of steel reinforcing bars where reinforced brick masonry is required (Figure 8.14).

Paving bricks (ASTM C902), used for the surfacing of walks, drives, and patios, must conform to requirements not only for freeze-thaw resistance, but water absorption and abrasion resistance as well. *Firebricks* (ASTM C64) are used for the lining of fireplaces or furnaces. These are made from special *fireclays* that produce bricks with refractory qualities (resistance to very high temperatures). Firebricks are laid in very thin joints of *fireclay mortar*.

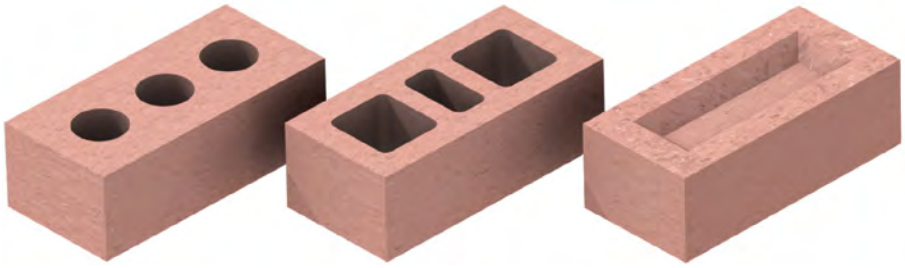


Figure 8.14
From left to right: **cored, hollow, and frogged bricks. Cored and frogged bricks are considered solid, as long as they remain at least 75 percent solid. A hollow brick may be up to 60 percent void.**

Brick Durability, Strength, and Appearance

Brick grade establishes levels of durability for bricks. Grade SW bricks have the highest minimum compressive strength and the lowest water absorption. Grades MW and NW bricks have progressively lower minimum strength requirements and higher water absorption rates. Together, these measures characterize bricks' resistance to *freeze-thaw weathering* (erosion of the brick body that occurs when absorbed water within the brick freezes and expands) and can be used to establish appropriate brick grades for different exposures (Figure 8.15).

A brick's compressive strength is also of obvious importance when used in the construction of loadbearing walls and piers. Minimum compressive strengths for building bricks and face bricks range, depending on the grade, from 1500 to 3000 pounds per square inch (psi) (10 to 21 MPa). However, higher-strength bricks are also readily available. A compressive strength of 10,000 psi (69 MPa) is not uncommon for bricks used in structural masonry. In high-strength applications, brick strength may exceed 20,000 psi (138 MPa). The strength of constructed brickwork depends not only on the strength of the bricks but also on the strength of the mortar and on the strength and quantity of reinforcing.

Brick type defines limits on the variation in size, distortion in shape, and *chippage* (extent of physical damage to face or visible corners) among brick units. Only facing brick and hollow brick are rated as to Type. Type FBS is a general-purpose face brick and the most common. Type FBX bricks have more stringent limits on uniformity and are intended for masonry work with very thin joints or for bond patterns demanding very close dimensional tolerances. Type FBA bricks are characterized by significant variations in size and shape, as is typical of handmade brick or brick intentionally manufactured for such effect. Hollow bricks are classified similarly, as listed in Figure 8.15.

Durability of Face Brick, Building Brick, and Hollow Brick	
Grade SW	Any weathering index (see Figure 8.16), brick above and below ground
Grade MW	Weathering index less than 50, brick above ground, and limited below ground applications
Grade NW (building brick only)	No exposure to water or freeze-thaw, brick above ground only
Appearance of Face Brick and Hollow Brick	
Type FBX (facing brick) Type HBX (hollow brick)	Least variation in size and shape, minimum chippage
Type FBS (facing brick) Type HBS (hollow brick)	General-purpose face brick, moderate variation in size and shape, greater chippage than Type FBX
Type FBA (facing brick) Type HBA, HBB (hollow brick)	Great nonuniformity in size and shape, as defined by manufacturer

FIGURE 8.15
Brick grade classifies durability. Brick type classifies appearance quality. Building bricks, which are not visible in the finished construction, are not classified for appearance. Weathering index ranges for the continental United States are shown in Figure 8.16.

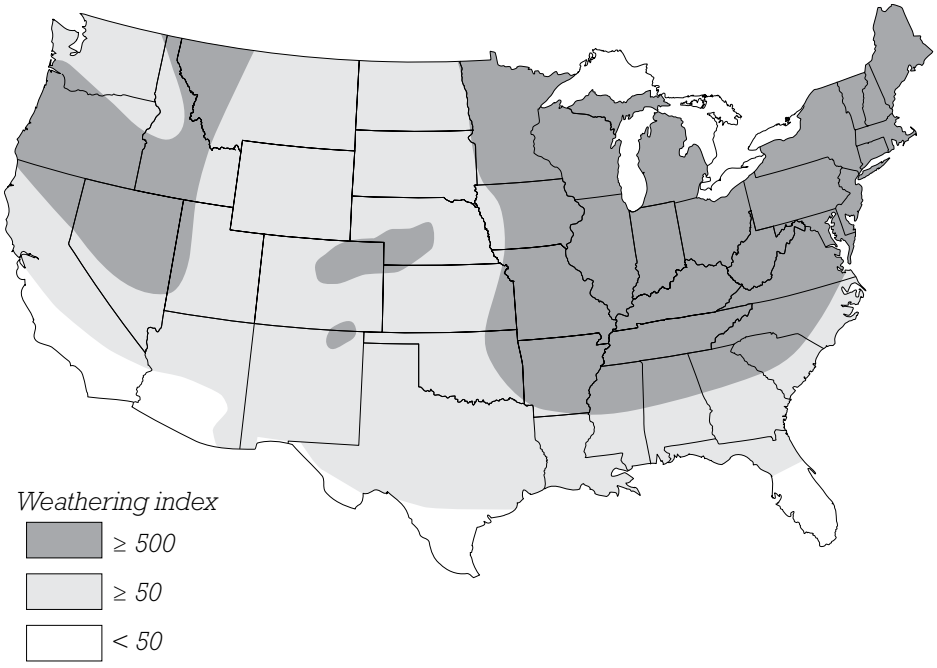


FIGURE 8.16
Weathering indices for the continental United States. Areas with higher indices receive greater amounts of winter rainfall and experience more freezing cycles. *(Adapted from the Brick Institute of America.)*

Brick Masonry

Laying Bricks

Figure 8.17 shows the vocabulary of bricklaying. The simplest brick wall is a single wythe of *stretcher courses*. For walls two or more wythes thick, headers are used to bond the wythes together. *Rowlock courses* are often used for caps on garden walls and for sloping sills under windows, although such caps and sills are not durable in severe climates. Architects frequently employ *soldier courses* for visual emphasis in such locations as window lintels or tops of walls.

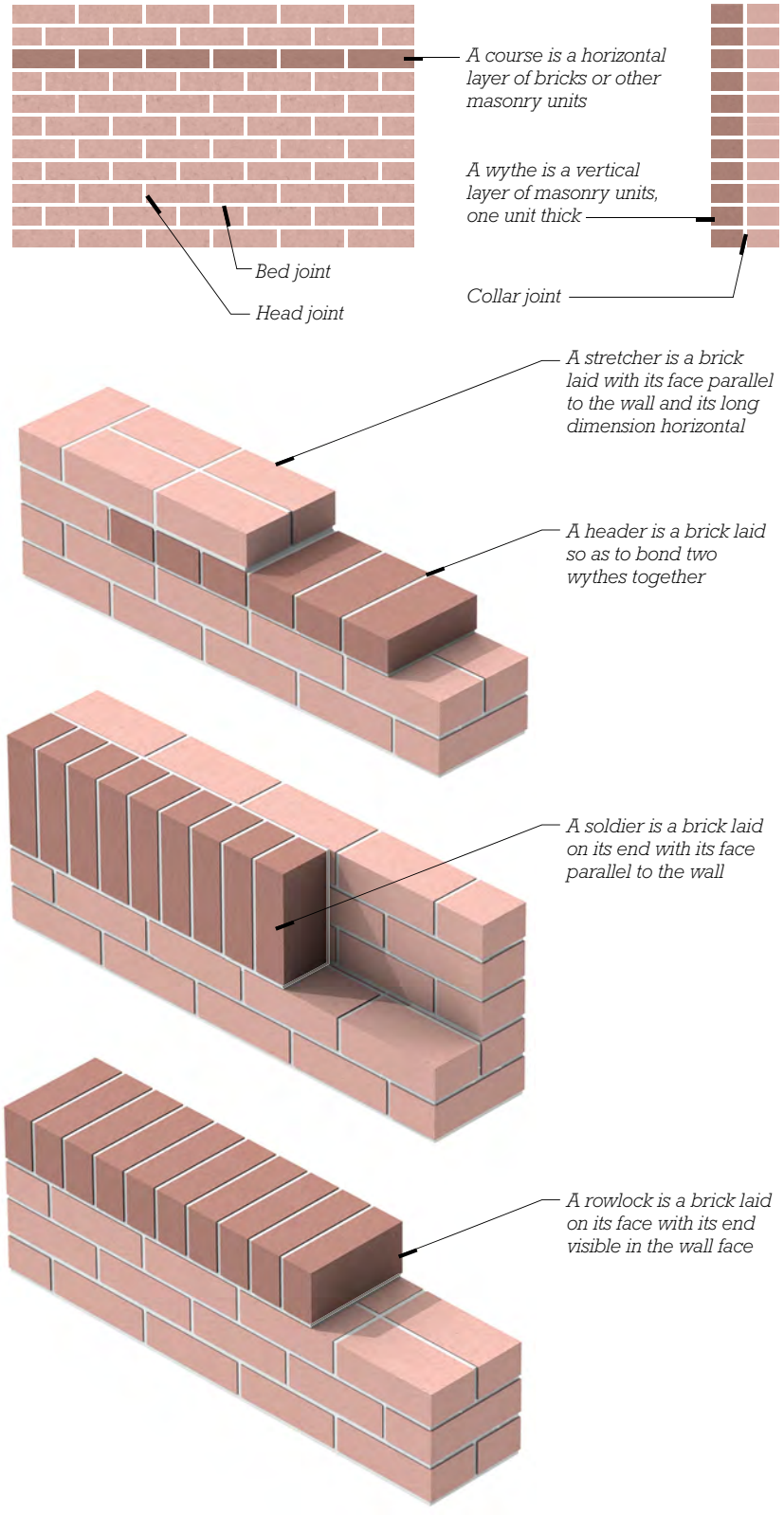
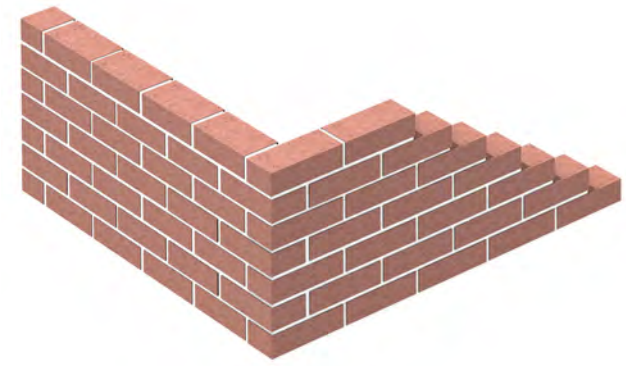


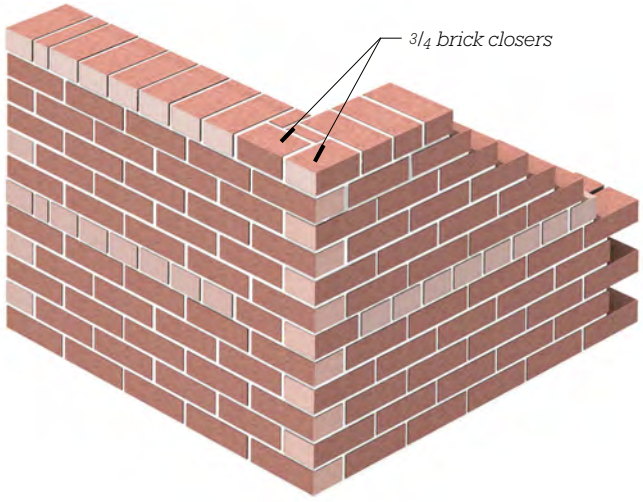
Figure 8.17
Basic brickwork terminology. A *course* is a single, horizontal row of bricks. A *head joint* is the mortar joint between two adjacent bricks in a course. A *bed joint* is the mortar joint between two courses. A *wythe* is a stack of brick courses, a vertical plane of brick only as wide as one brick unit. A *collar joint* is the mortar joint between two wythes. The basic brick positions of *stretcher*, *header*, *soldier*, and *rowlock* are also illustrated.

Historically, the problem of bonding multiple wythes of brick has been solved in many ways in different regions of the world, often resulting in surface patterns that are particularly pleasing to the eye. Figures 8.18 and 8.19 show some *structural bonds* for brickwork, among which *common bond*, *Flemish bond*, and *English bond* are the most popular. In modern masonry wall construction, *running bond* is the most frequently used bond, as it is the most economical to construct. Today, where structural bonds are used, they are chosen mainly for their aesthetic qualities, and bonding between wythes is achieved with various types of metal ties or reinforcing (see Chapter 10).

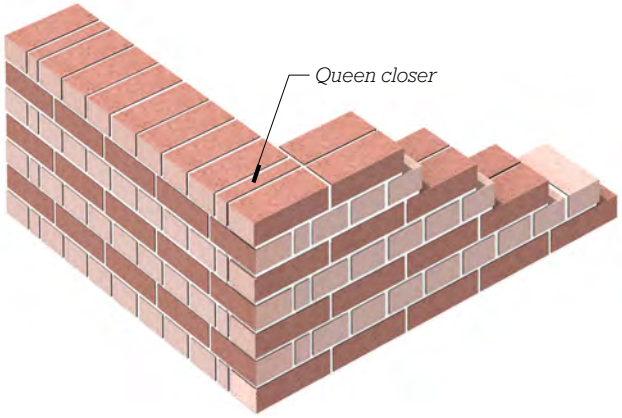
The process of bricklaying is summarized in Figures 8.20 and 8.21. While conceptually simple, bricklaying requires both extreme care and considerable experience to produce a satisfactory result, especially where a number of bricklayers working side by side must produce identical work on a major structure. Yet speed is essential to the economy of masonry construction. The work of a skilled mason is impressive both for its speed and for its quality. This level of expertise takes time and hard work to acquire, which is why the apprenticeship period for brick masons is both long and demanding.



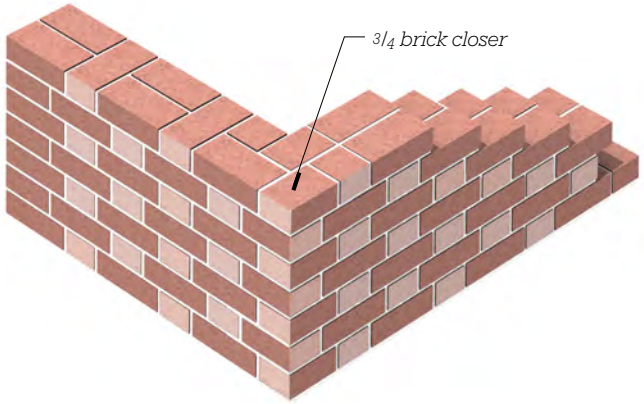
Running Bond consists entirerly of stretchers



Common Bond (also known as American Bond) has a header course every sixth course. Notice how the head joints are aligned between the header and the stretcher courses



English Bond alternates courses of headers and stretchers

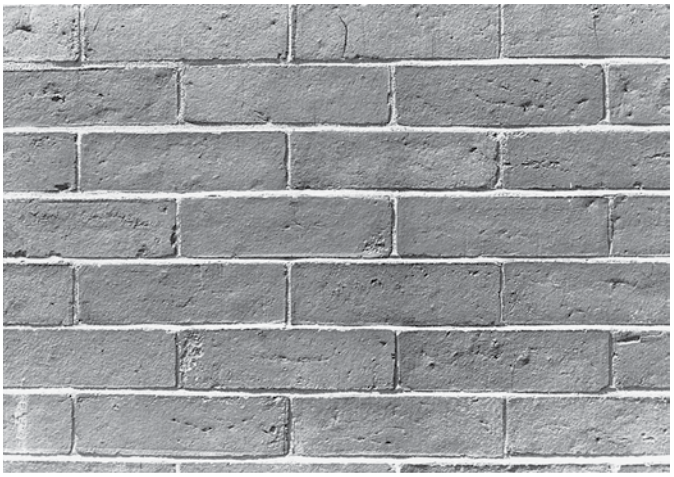


Flemish Bond alternates headers and stretchers in each course

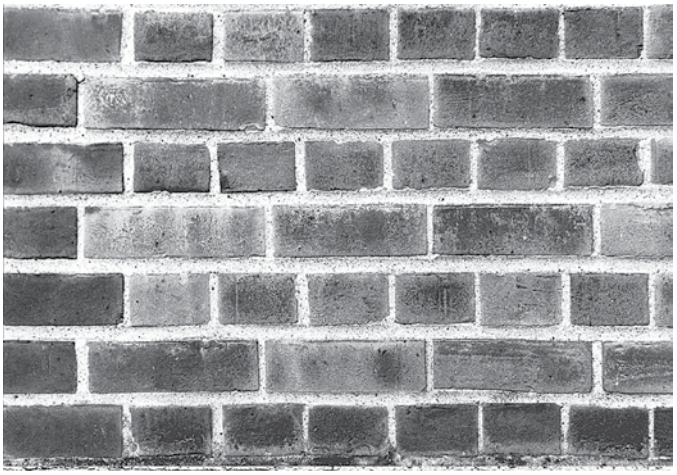
FIGURE 8.18

Frequently used bonds for brick walls. Running bond is not a structural bond. The other bonds illustrated are all structural bonds. In these, partial closer bricks are necessary at the corners to make the header courses come out even while avoiding alignments of head joints in successive courses. The mason cuts the closers to length with a mason's hammer or diamond saw.

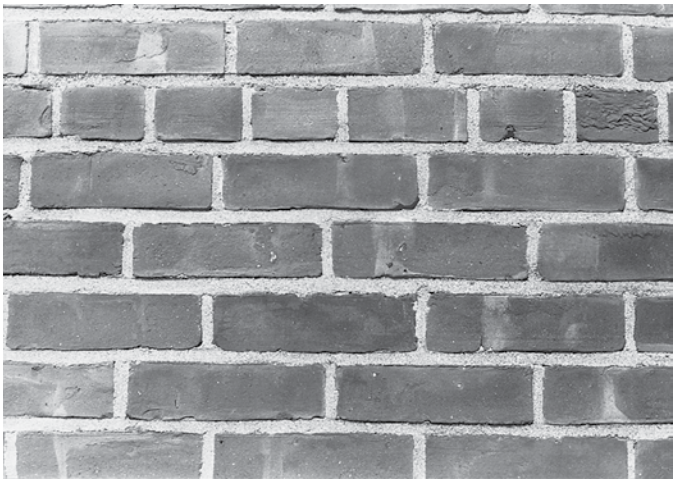
Interactive Exercise



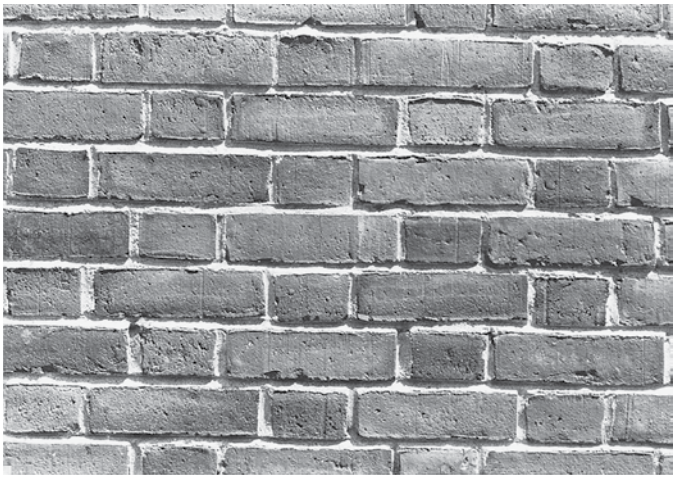
(*a*)



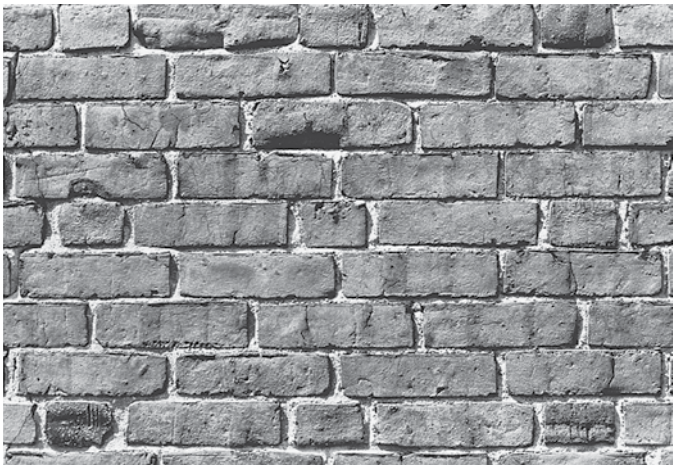
(*d*)



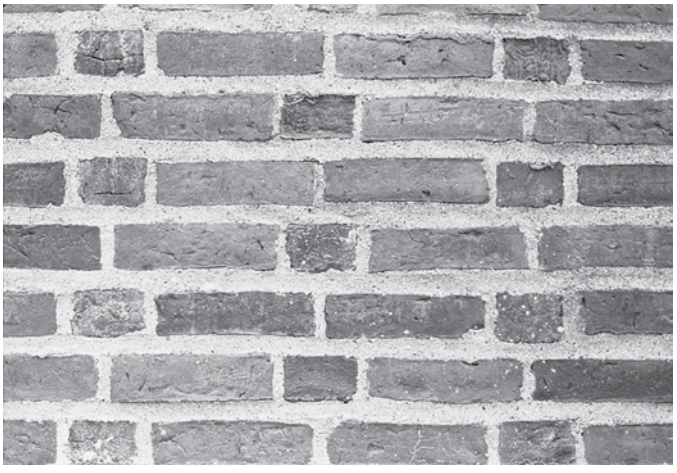
(*b*)



(*e*)



(*c*)



(*f*)

FIGURE 8.19
Photographs of some brick bonds. (*a*) Running bond, (*b*) common bond, and (*c*) English garden wall bond with Flemish header courses. In the right column, (*d*) English bond, (*e*) Flemish bond, and (*f*) monk bond, which is a Flemish bond with two stretchers instead of one between headers. The running bond example shown here is from the late 18th century. Its extremely thin joints require mortar made with very fine sand. Notice in the common bond wall (dating from the 1920s in this case) that the header course began to fall out of alignment with the stretcher courses, so the mason inserted a partial stretcher to make up the difference; such small variations in workmanship account for some of the visual appeal of brick walls. Flemish header courses, such as those used in the English garden wall bond, are often used with bricks whose length, including mortar joint, is substantially more than twice their width; the Flemish header course avoids the thick joints between headers that would otherwise result. The Flemish bond example is modern and is composed of modular sand-mold bricks. The monk bond shown here has unusually thick bed joints, approximately ¾ inches (19 mm) high; these joints are difficult for the mason to lay unless the consistency of the mortar is very closely controlled. *(Photos by Edward Allen.)*

The laying of *leads* (pronounced "leeds") is relatively labor intensive. A mason's rule or a *story pole* that is marked with the course heights is used to establish accurate course heights in the leads. The work is checked frequently with a spirit level to ensure that surfaces are flat and plumb and courses are level. When the leads have been completed, a mason's line (a heavy string) is stretched between the leads, using L-shaped *line blocks* at each end to locate the end of the line precisely at the top of each course of bricks.

The laying of the infill bricks between the leads is much faster and easier because the mason needs only a trowel in one hand and a brick in the other to *lay to the line* and create a perfect wall. It follows that leads are expensive compared to the wall surfaces between them, so where economy is important, the designer should seek to minimize the number of corners in a brick structure.

Bricks may be cut as needed, either with sharp, well-directed blows of the chisel-pointed end of a mason's hammer or, for greater accuracy and more intricate shapes, with a power saw that utilizes a water-cooled diamond blade (see Figure 9.22). Cutting of bricks slows the process of bricklaying considerably, however, and ordinary brick walls should be dimensioned to minimize cutting wherever possible (Figure 8.22).

I remember the masons on my first house. I was not much older than the apprentice whom I found choking back tears of frustration with the clumsiness of his work and the rebukes of his boss.

Nearly thirty years later, we still collaborate on sometimes difficult masonry walls, fireplaces and paving patterns. I work with bricklayers . . . whose years of learning their craft paralleled my years of trying to understand my profession. We are friends and we talk about our work like pilgrims on a journey to the same destination.

—Henry Klein, architect, at his acceptance of the Louis Sullivan Award for Architecture, 1981, quoted in *Blueprints Magazine*, 1985

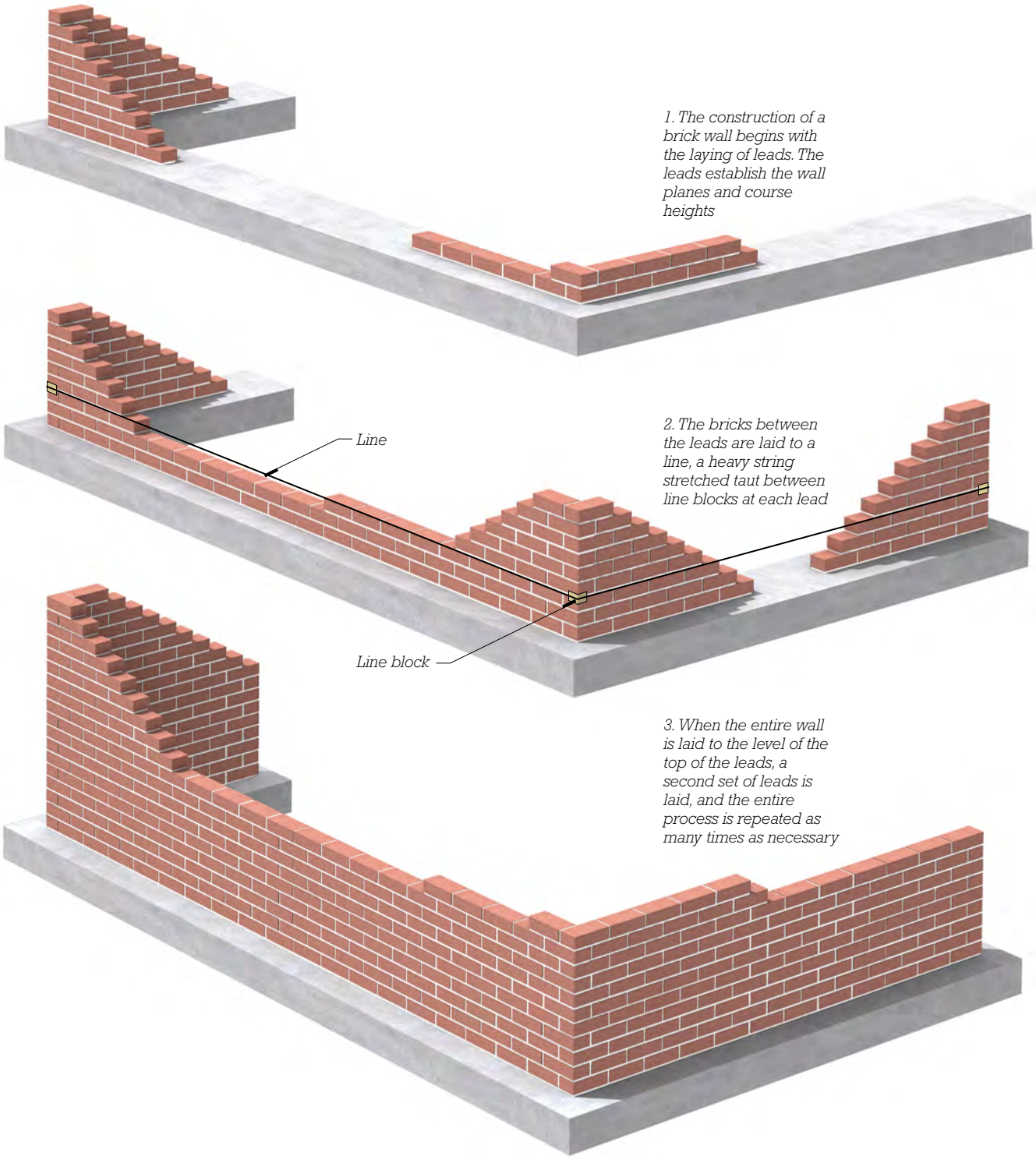
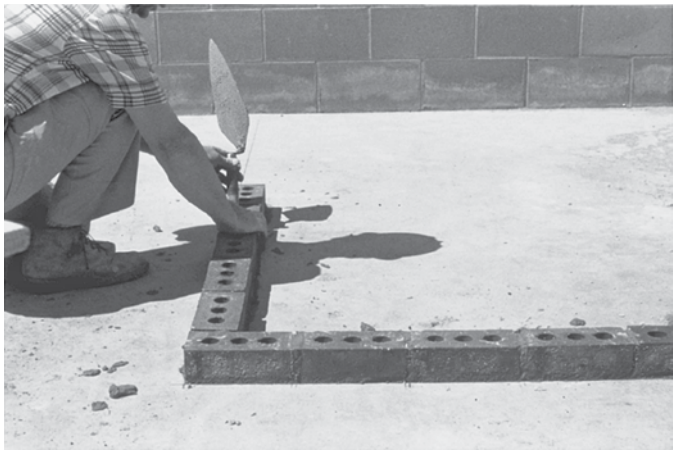
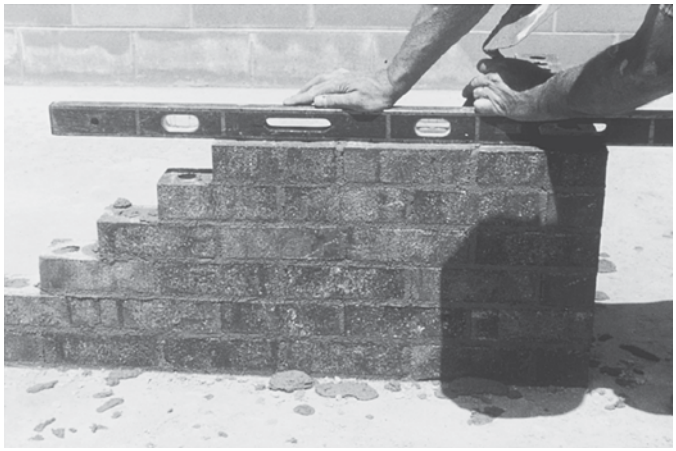


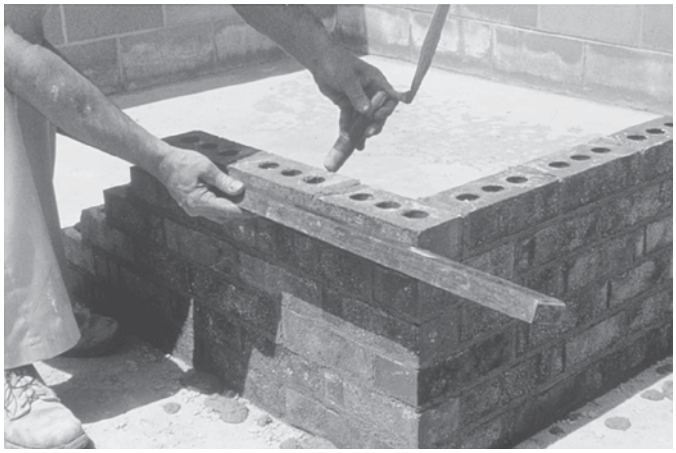
FIGURE 8.20
The procedure for building brick walls. This example is a single wythe of running bond.



(*a*)



(*b*)



(*c*)

(*d*)

(*e*)

(*f*)

FIGURE 8.21

Laying a brick wall. (*a*) The first course of bricks for a lead is bedded in mortar, following a line marked on the foundation. (*b*, *c*, *d*) As each lead is built higher, the mason uses a spirit level to make sure that each course is level, straight, plumb, and in the same plane as the rest of the lead. A mason's rule or a story pole is also used to check the heights of the courses. (*e*) A finished lead. (*f*) A mason lays brick to a line stretched between two leads. When laying to a line, there is no need to use a level or rule. *(Courtesy of International Masonry Institute, Washington, DC.)*

Mortar joints can vary in thickness from less than ¼ inch (6 mm) to more than ½ inch (13 mm). Thin joints work only when the bricks are identical in size to one another within very small tolerances and the mortar is made with fine sand. Very thick joints require a stiffer than normal mortar that is difficult to work with. Mortar joints in the range of ⅜ to ½ inch (10 to 13 mm) thick coordinate with the dimensioning of modular bricks, are easy for the mason to work with, and readily accommodate the normal distortion and unevenness found in most bricks.

The joints in brickwork are *tooled* an hour or two after laying as the mortar begins to harden, to give a neat appearance and to compact the mortar into a profile that meets the visual and weather-resistive requirements of the wall (Figures 8.23 and 8.24). Outdoors, the *vee joint* and *concave joint* shed water and resist freeze-thaw damage better than the others. Indoors, *raked*, *stripped*, or *struck joints* can be used if desired to accentuate the pattern of bricks in the wall in various ways.

After joint tooling, the face of the brick wall is swept with a soft brush to remove the dry crumbs of mortar left by the tooling process. If the mason has worked cleanly, the wall is now finished, but most brick walls are given a final cleaning by scrubbing with weak *muriatic acid* (hydrochloric acid) or another cleaning agent and rinsing with water to remove mortar stains from the faces of the bricks.

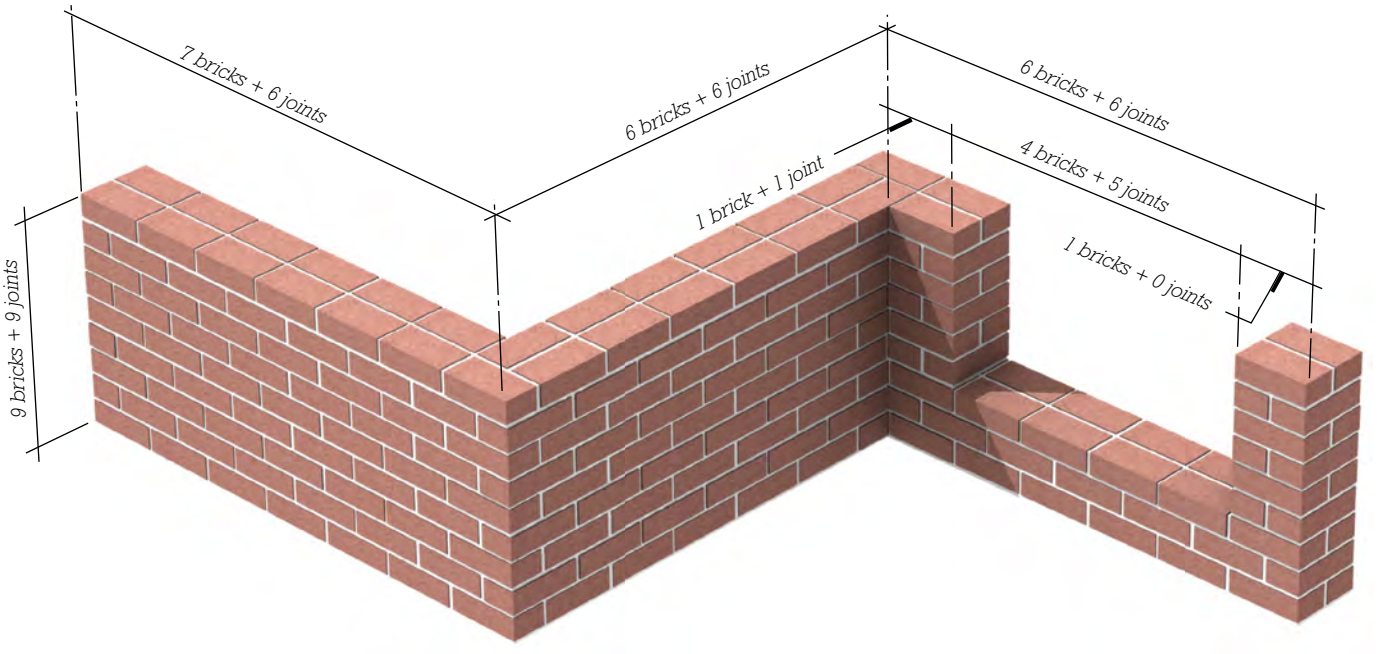
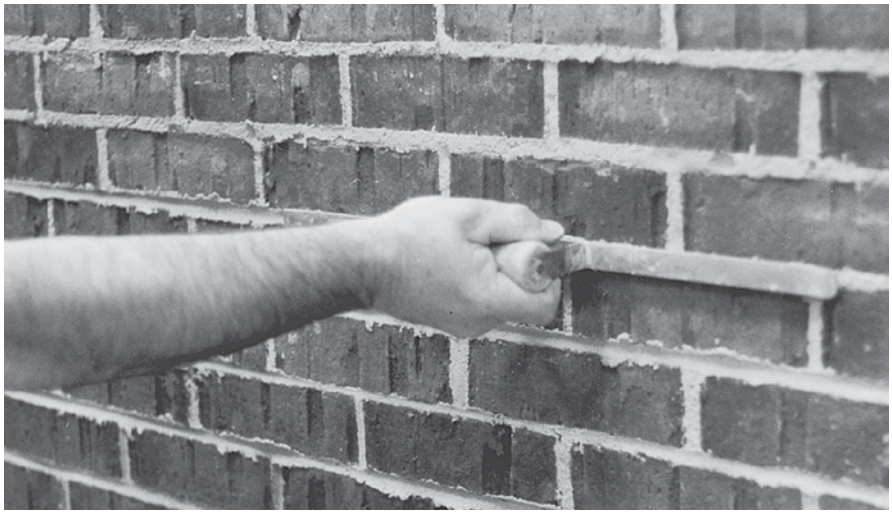


FIGURE 8.22
Dimensions for brick buildings are worked out in advance by the architect based on the actual dimensions of the bricks and the mortar joints to be used in the building. Bricks and mortar joints are carefully counted and converted to numerical dimensions for each portion of the wall.

Interactive Exercise

FIGURE 8.23
(*a*) Tooling horizontal joints to a concave profile. (*b*) Tooling vertical joints to a concave profile. The excess mortar squeezed out of the joints by the tooling process will be swept off with a brush, leaving a finished wall. (*c*) Raking joints with a common nail held in a skate-wheel joint raker. The head of the nail digs out the mortar to a preset depth. *(Courtesy of Brick Institute of America.)*



(*a*)

(*b*)

(*c*)

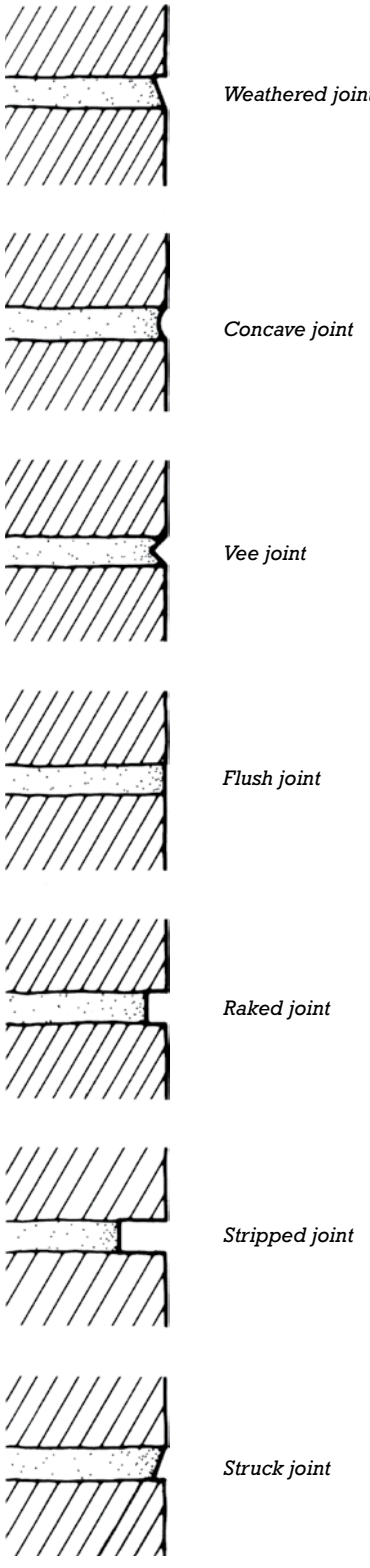


FIGURE 8.24
Joint tooling profiles for brickwork. The concave joint and vee joint are the only ones suitable for outdoor use in severe climates.

Spanning Openings in Brick Walls

Brick walls must be supported above openings for windows and doors. *Lintels* of reinforced concrete, reinforced brick, or steel angles (Figures 8.25 and 8.26) are all equally satisfactory from a technical standpoint. The near invisibility of the steel lintel is a source of delight to some designers but dissatisfies those who prefer that a building visually express its means of support.

The *corbel* is an ancient structural device of limited spanning capability, one that may be used for small openings in brick walls, for beam brackets, and for ornament (Figures 8.27, 8.28, and 8.29). A good rule of thumb for designing corbels is that the projection of each course should not exceed half the course height; this results in a corbel angle of about 60 degrees to the horizontal and minimizes flexural stress in the bricks.

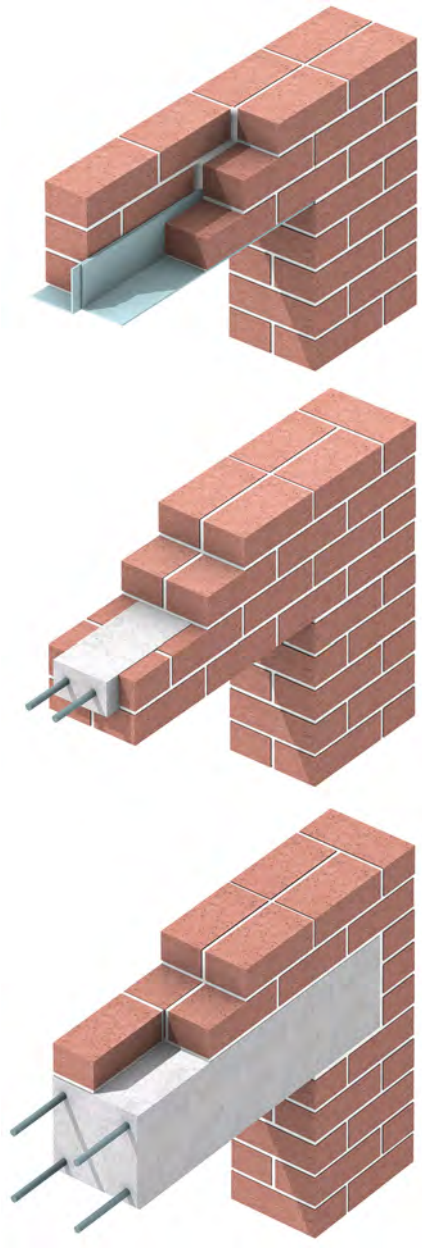


FIGURE 8.25
Three types of lintels for spanning openings in brick walls. The double-angle steel lintel (*top*) is scarcely visible in the finished wall. The reinforced brick lintel (*center*) works in the same manner as a reinforced concrete beam and gives no visible clues as to what supports the bricks over the opening. The precast reinforced concrete lintel (*bottom*) is clearly visible. For short spans, cut stone lintels without reinforcing can be used in the same manner as concrete lintels.

Interactive Exercise

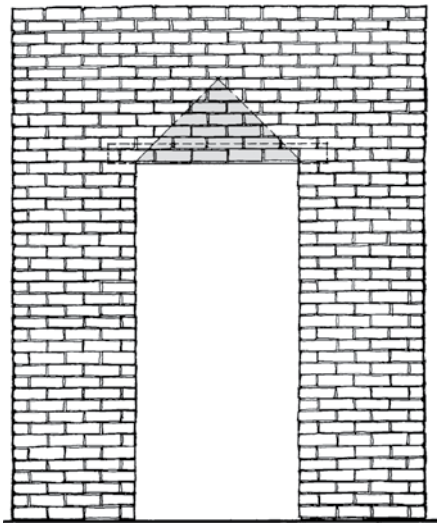


FIGURE 8.26
Because of corbelling and arching action in the bricks, a lintel is considered to carry only the triangular area of brickwork indicated by the shaded portion of this drawing. The broken line indicates a concealed steel angle lintel.

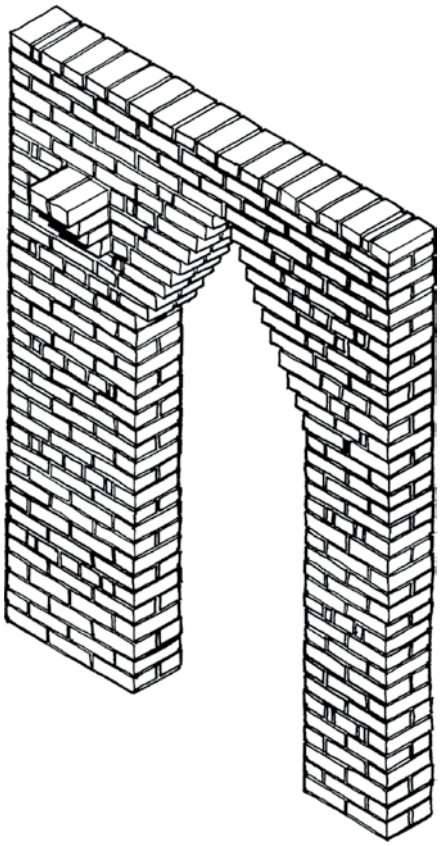


Figure 8.27
Corbelling has many uses in masonry construction. It is used in this example both to span a door opening and to create a bracket to support a beam.

Figure 8.28
Corbelling creates a transition from the cylindrical tower to a hexagonal roof. Cut limestone is used for windowsills, lintels, arch intersections, and grotesquely carved rainwater spouts. The building is the Gothic cathedral in Albi, France. *(Photo by Edward Allen.)*

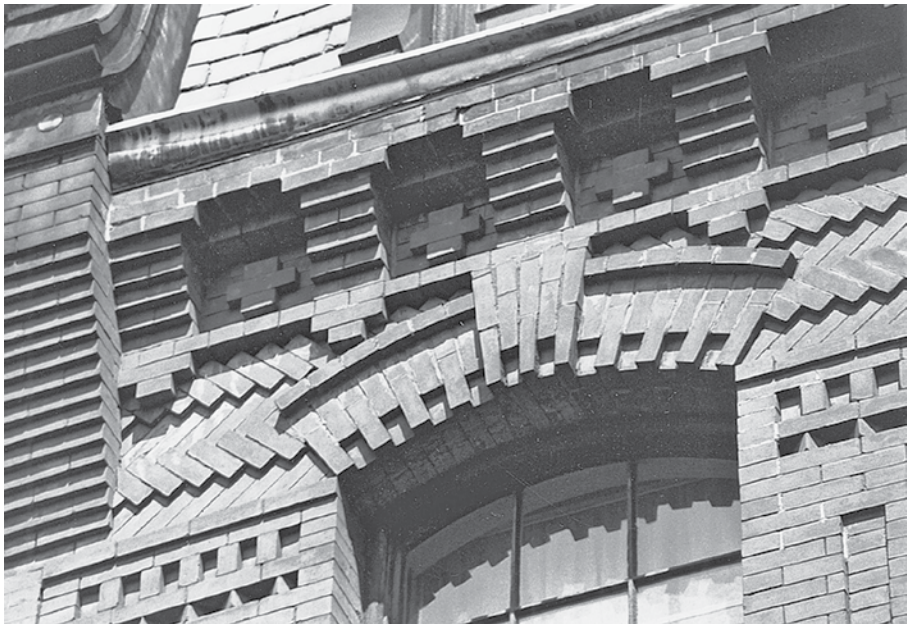
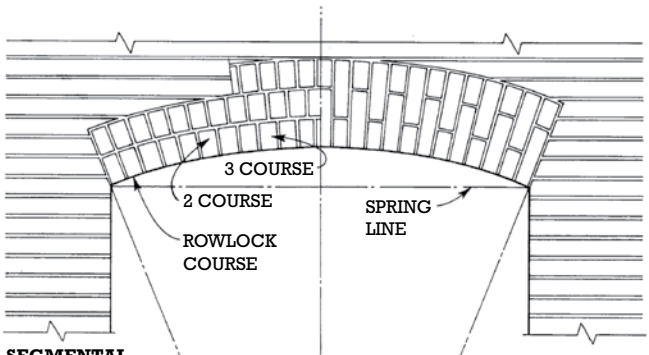
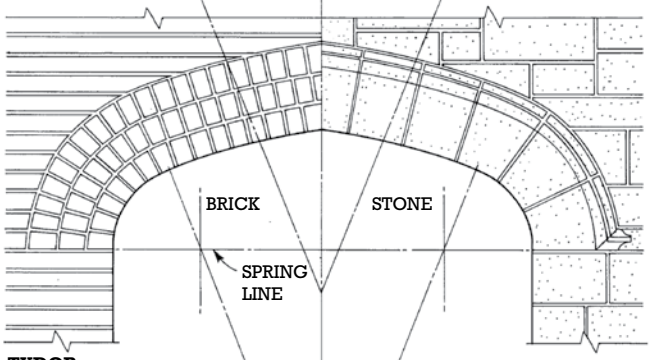


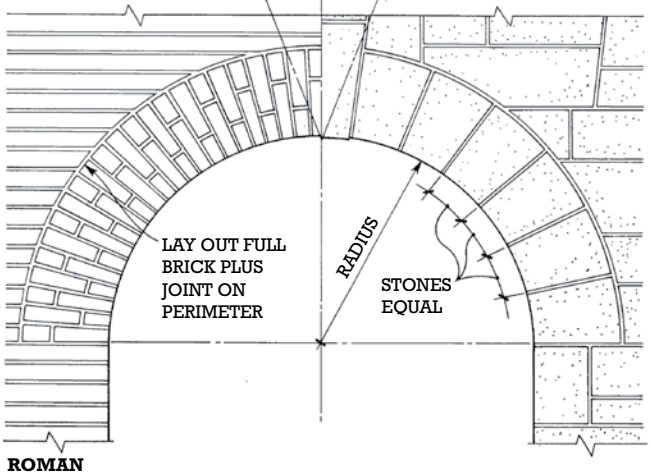
Figure 8.29
All the skills of the 19th-century mason were called into play to create the corbels and arches of this brick cornice in Boston's Back Bay. *(Photo by Edward Allen.)*



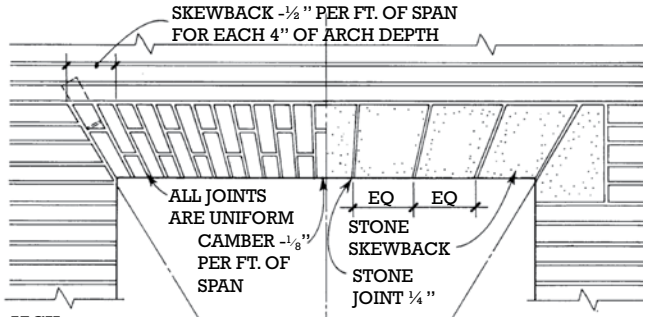
SEGMENTAL



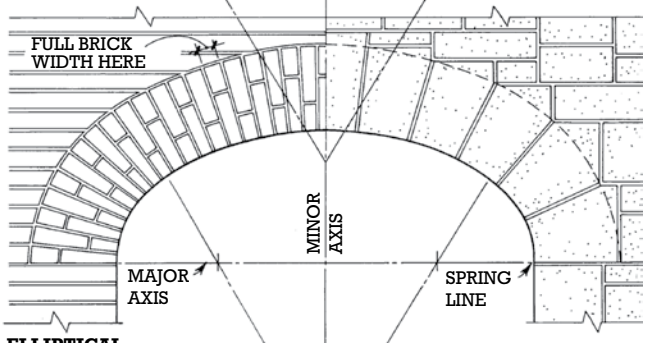
TUDOR



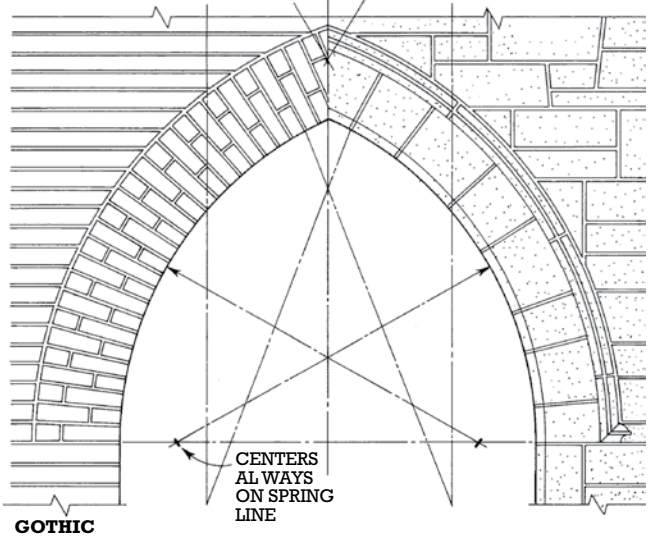
ROMAN



JACK

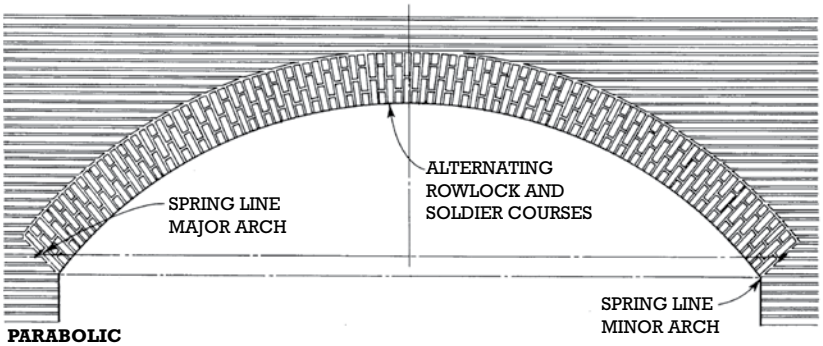


ELLIPTICAL

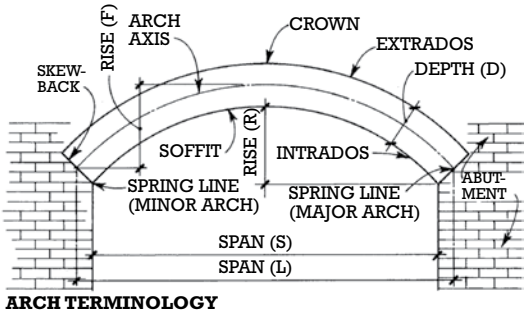


GOTHIC

NOTE: Stone joints may be handled in a variety of ways. This is one illustration.



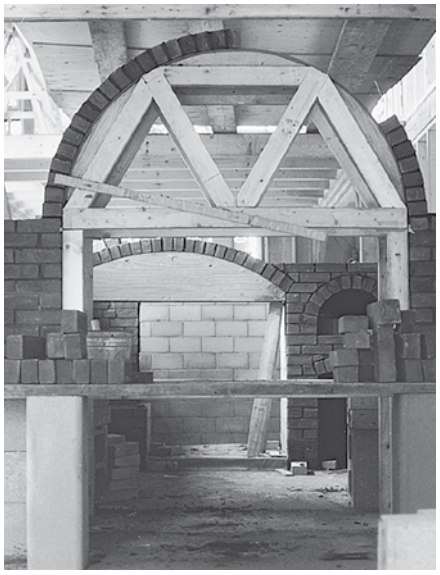
PARABOLIC



ARCH TERMINOLOGY

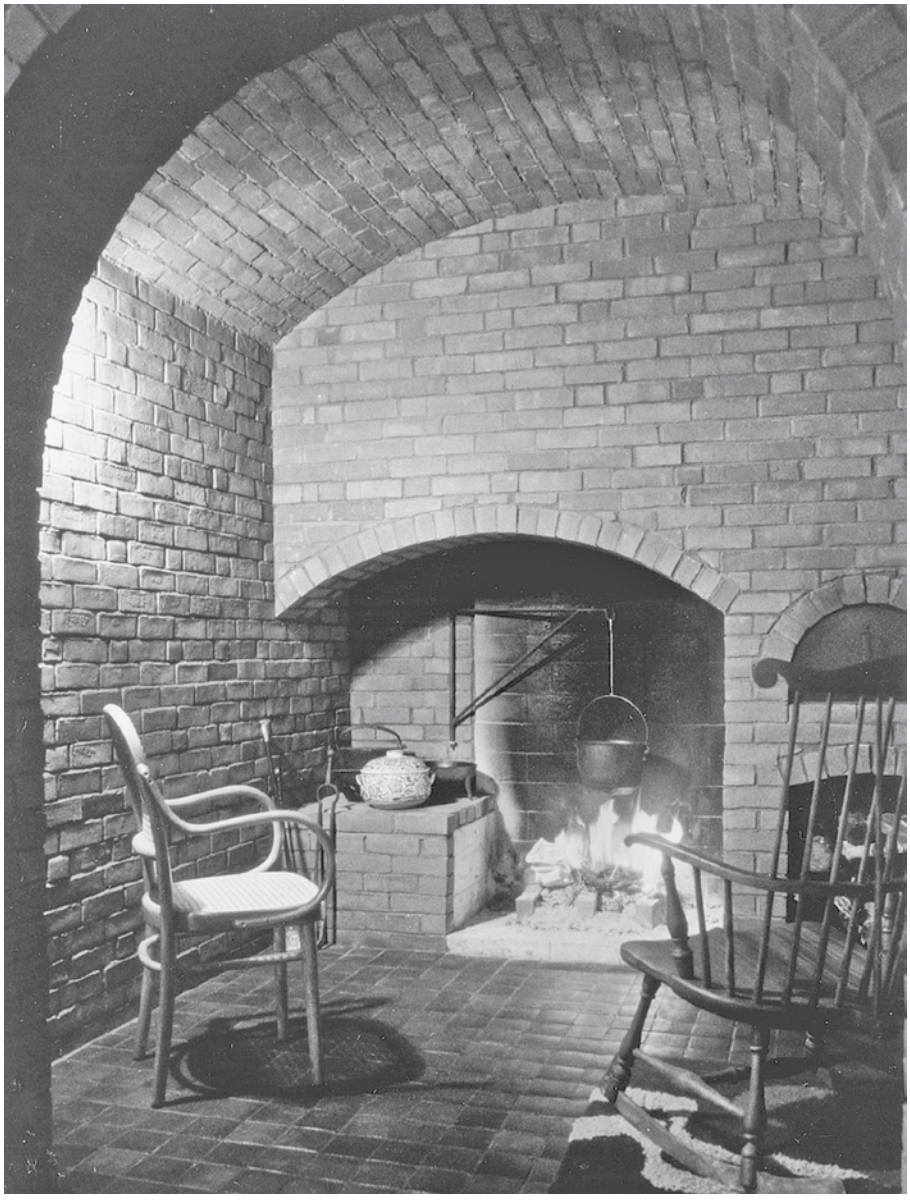
FIGURE 8.30
Arch forms and arch terminology in brick and cut stone. The spandrel is the area of wall that is bounded by the extrados of the arch. *(Reprinted by permission of John Wiley & Sons from Ramsey/Sleeper,* Architectural Graphic Standards, *7th ed., Robert T. Packard, A.I.A., ed., © 1981 by John Wiley & Sons.)*

The brick *arch* is a structural form so widely used and so powerful, both structurally and symbolically, that entire books have been devoted to it (Figure 8.30). Given a *centering* of wood or steel (Figure 8.31), a mason can lay a brick arch rapidly, although the *spandrel*, the area of flat wall that adjoins the arch, is time-consuming to construct because many of its bricks must be cut to fit. In an arch of *gauged brick*, each brick is rubbed to the required wedge shape on an abrasive stone, which is laborious



(*a*)

(*b*)



(*c*)

FIGURE 8.31
(*a*) Two rough brick arches under construction, each on its wooden centering. (*b*) The brick locations were marked on the centering in advance to be sure that no partial bricks or unusual mortar joint thicknesses will be required to close the arch. This was done by laying the centering on its side on the floor and placing bricks around it, adjusting their positions by trial and error to achieve a uniform spacing. Then the location of each brick was marked with pencil on the curved surface of the centering. (*c*) The brick arches whose construction is illustrated in the previous two photographs span a fireplace room that is roofed with a brick barrel vault. The firebox is lined with firebrick, and the floor is finished with quarry tiles. *(Photo by Edward Allen.)*

and expensive. The *rough arch*, which depends on wedge-shaped mortar joints for its curvature, is therefore much more usual in today's buildings (Figures 8.32 and 8.33). A number of brick manufacturers will mold to order sets of tapered bricks for arches of any shape and span.

An arch translated along a line perpendicular to its plane produces a *barrel vault*. An arch rotated around its vertical centerline becomes a *dome*. From various intersections of these two basic roof shapes comes the infinite vocabulary of vaulted masonry construction. Brick vaults and domes, if their lateral thrusts are sufficiently tied, or *buttressed*, are strong, stable forms. In parts of the world where labor is inexpensive, they continue to be built on an everyday basis (Figures 8.34 and 8.46). In North America and most of Europe, where labor is more costly, they have been replaced almost entirely by less expensive, more compact spanning elements, such as beams and slabs of wood, steel, or concrete.

FIGURE 8.32
A deep semicircular brick arch frames a view of a brick arcade and the harbor beyond at the Moakley Federal Courthouse in Boston. *(Architect: Pei Cobb Freed & Partners. Photo © Steve Rosenthal, 1998.)*

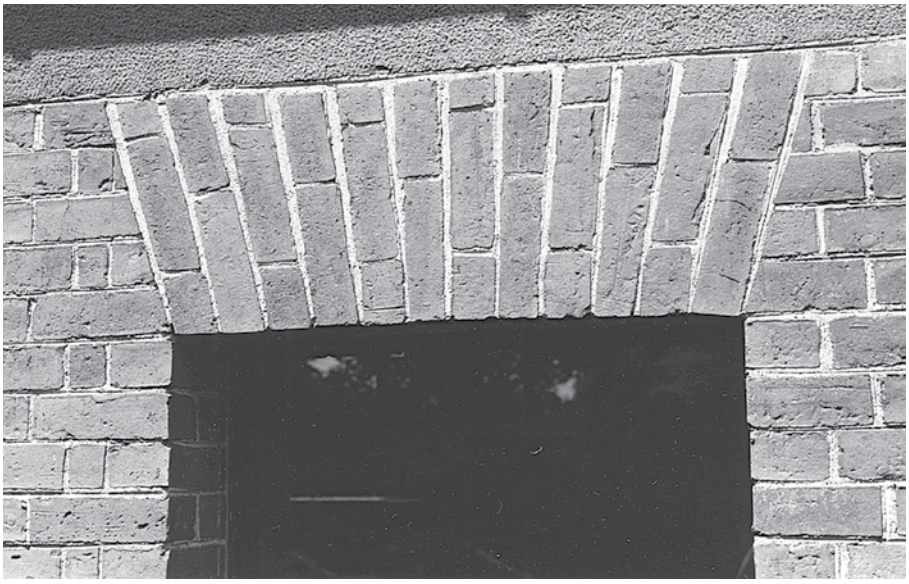
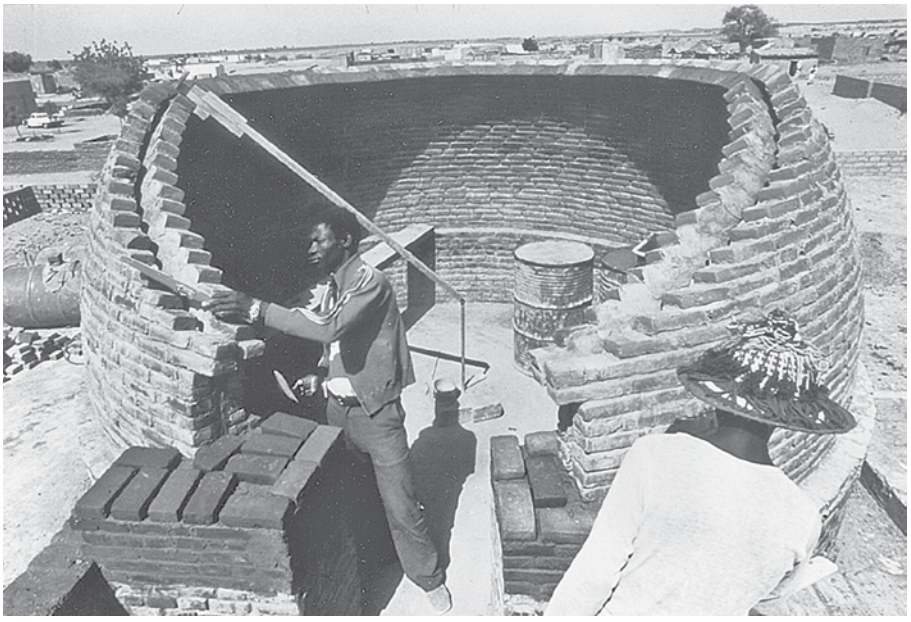


FIGURE 8.33
A rough *jack arch* (also called a *flat arch*) in a wall of Flemish bond brickwork. *(Photo by Edward Allen.)*



(*a*)

(*b*)

FIGURE 8.34

(*a*) Masons in Mauritania, drawing on thousands of years of experience in masonry vaulting, build a dome for a patient room of a new hospital. The masonry is self-supporting throughout the process of construction; only a simple radius guide is used to maintain a constant diameter. The dome is double, with an airspace between to insulate the room from the sun's heat. (*b*) The walls are buttressed with stack bond brick headers to resist the outward thrust of the domes. *(Courtesy of ADAUA, Geneva, Switzerland.)*

Reinforced Brick Masonry

Reinforced brick masonry (*RBM*) is analogous to reinforced concrete construction. The same deformed steel reinforcing bars used in concrete (see Chapter 13) are placed in thickened collar joints or the cores of hollow brick to strengthen a brick wall or lintel. A reinforced brick wall (Figure 8.35) is normally created by constructing two wythes of brick 2 to 4 inches (50 to 100 mm) apart, placing the reinforcing steel in the cavity, and filling the cavity with *grout*. Grout is a mixture of portland cement, aggregate, and water. ASTM C476 specifies the proportions and qualities of grout for use in filling masonry loadbearing walls. It is important that grout be fluid enough to flow readily into the narrow cavity and fill it completely. The excess water in the grout that is required to achieve this fluidity is quickly absorbed by the bricks and does not detract from the eventual strength of the grout, as it would from concrete poured into formwork. Highly flowable *self-consolidating grout*, analogous to self-consolidating concrete as described in Chapter 13, can also be used.

There are two methods for grouting reinforced brick walls: low lift and high lift. In *low-lift grouting*, the masonry is constructed to a height not greater than 4 feet (1200 mm) before grouting, taking care to keep the cavity free of mortar squeeze-out and droppings, which might interfere with the placement of the reinforcing and grout. The vertical reinforcing bars are inserted into the cavity and are left projecting at least 30 bar diameters above the top of the brickwork to transfer their loads to the steel in the next lift. The cavity is then filled with grout to within 1½ inch (38 mm) of the top, and the process is repeated for the next lift.

In *high-lift grouting*, the wall is grouted a story at a time. The cleanliness of the cavity is ensured by temporarily omitting some of the bricks in the lowest course of masonry to create *cleanout holes*. As the bricklaying progresses, the cavity is flushed periodically from above with water to drive debris down and out through the cleanouts. To resist the hydrostatic pressure of the wet grout, the wythes are held together by galvanized steel wire *ties* laid into the bed joints and across the cavity, usually at intervals of 24 inches (600 mm) horizontally and 16 inches (400 mm) vertically. After the cleanouts have been filled with bricks and the mortar has cured for at least three days, the reinforcing bars are placed and grout is pumped into the cavity from above in increments not more than 4 feet (1200 mm) high. To minimize pressure on the brickwork, each increment is allowed to harden for an hour or so before the next increment is poured above it.

The low-lift method is generally easier for smaller projects where the grout is poured by hand. Where grout-pumping equipment must be rented, the high-lift method is preferred because it minimizes rental costs.

Although unreinforced brick walls were once adequate for structural purposes, reinforced brick masonry walls are much stronger and better able to resist gravity loads, flexural loads from wind or earth pressure, and the dynamic stresses of earthquakes. With RBM, it is possible to build bearing wall buildings to heights formerly possible only with steel and concrete frames, and to do so with surprisingly thin walls (Figures 8.36 and 8.37). RBM is also used for brick piers, which are analogous to concrete columns, and, less commonly, for structural lintels (Figure 8.25), beams, slabs, and retaining walls.

Reinforced brickwork may also be created at a smaller scale by inserting reinforcing bars and grout into the cores of hollow bricks. This technique is especially useful for single-family residential construction and for single-wythe prefabricated curtain wall panels (Chapter 20).

FIGURE 8.35
A reinforced brick loadbearing wall is built by installing steel reinforcing bars in a thickened collar joint, then filling the joint with portland cement grout. The cleanout holes shown here are used in the high-lift method of grouting.

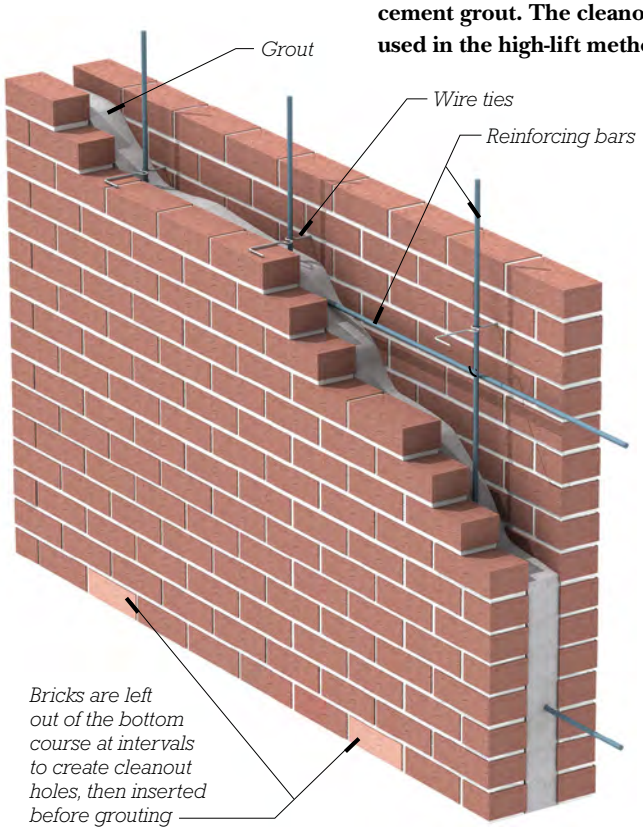


Figure 8.36
Twelve-inch (300-mm) reinforced brick walls of constant thickness bear the concrete floor and roof structures of a hotel. (*Photo by Edward Allen.*)

Masonry Wall Construction

Brick, stone, and concrete masonry units are mixed and matched in both loadbearing and nonloadbearing walls of many types. Stone and concrete masonry are discussed in Chapter 9, and the more important types of masonry wall constructions are presented in Chapter 10. Figures 8.38 through 8.46 illustrate just some of the richness and stylistic diversity possible with brick masonry construction.

Figure 8.37
Because loads in a building accumulate from top to bottom, the unreinforced brick walls of the 16-story Monadnock Building, built in Chicago in 1891, are 18 inches (460 mm) thick at the top and 6 feet (1830 mm) thick at the base of the building. (*Nicholas Janberg, **www.structurae.de***)

Figure 8.38
Ornamental corbelled brickwork in an 18th-century New England chimney. Step flashings of lead-sheet waterproof the junction between the chimney and the wood shingles of the roof. *(Photo by Edward Allen.)*

Interactive Exercise

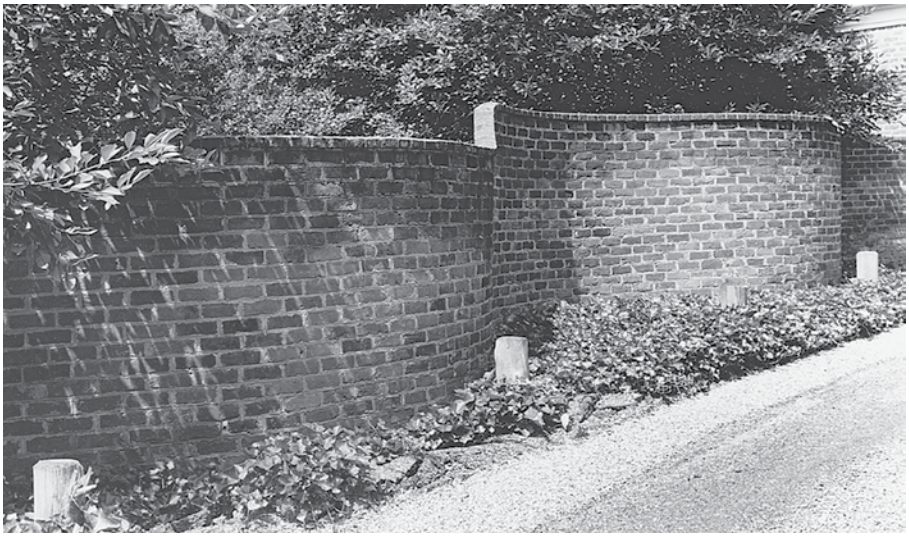


Figure 8.39
In the gardens he designed at the University of Virginia, Thomas Jefferson used unreinforced serpentine walls of brick that are only a single wythe thick. The shape of the wall makes it extremely resistant to overturning despite its thinness. *(Photo by Wayne Andrews.)*

FIGURE 8.40
Cylindrical bays of brick with stone lintels front these Boston rowhouses.
(Photo by Edward Allen.)

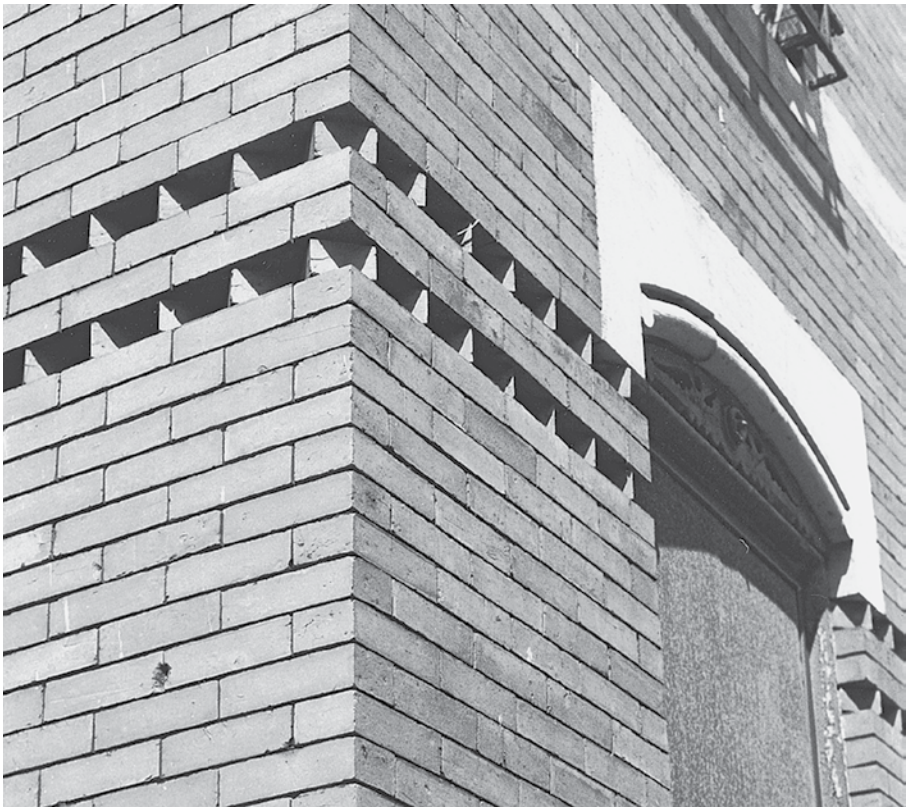


FIGURE 8.41
Bricks were laid diagonally in two of the courses to create this mouse-tooth pattern. The window is spanned with a segmental arch of cut limestone. *(Photo by Edward Allen.)*

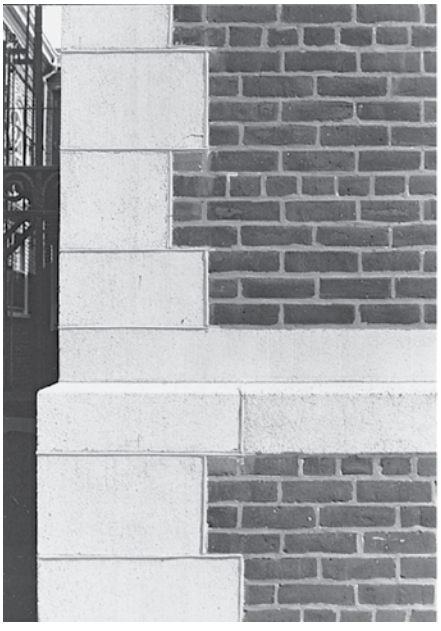


FIGURE 8.42
Quoins **originated long ago as cut-stone blocks used to form strong corners on walls of weak masonry materials, such as mud bricks or round fieldstones. In more recent times, quoins (pronounced "coins") have been used largely for decorative purposes. At the left, cut limestone quoins and a limestone *water table* dress up a common bond brick wall. The mortar joints between quoins are finished in a protruding beaded profile to emphasize the pattern of the stones. At the right, brick quoins are used to make a graceful termination of a concrete masonry wall at a garage door opening. Notice that three brick courses perfectly match one block course.** *(Photo by Edward Allen.)*

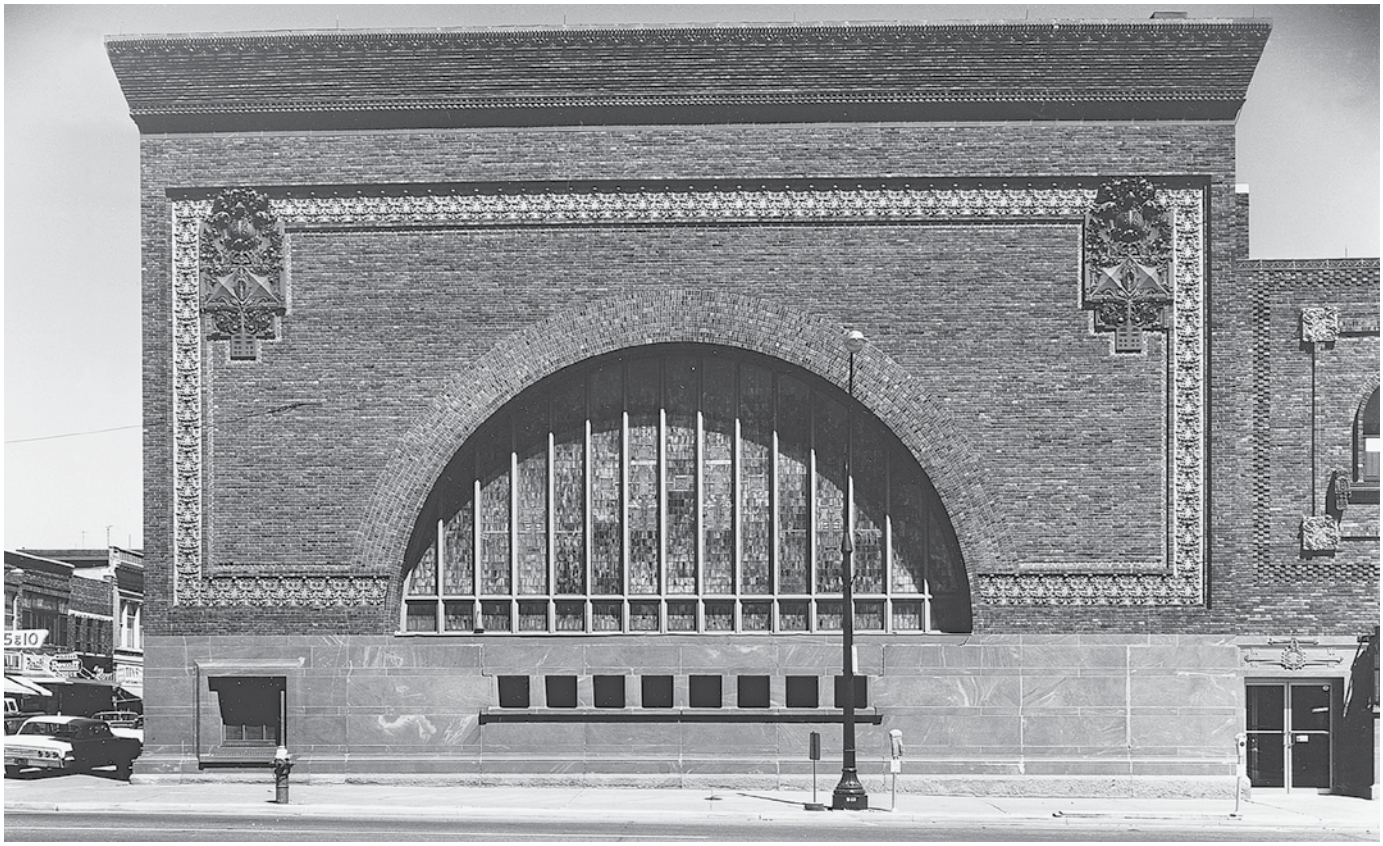


Figure 8.43
Louis Sullivan's National Farmers' Bank in Owatonna, Minnesota, completed in 1908, rises from a red sandstone base. Enormous rowlock brick arches span the windows in the two street facades. Bands of glazed terra-cotta ornament in rich blues, greens, and browns outline the walls, and a flaring cornice of corbelled brick and terra cotta caps the building. *(Photo by Wayne Andrews.)*

Figure 8.44
Architect Pei Cobb Freed & Partners employed brick half-domes to mark the entrances to courtrooms in the Moakley Federal Courthouse in Boston. *(Photo © Steve Rosenthal, 1998.)*

FIGURE 8.45
Frank Lloyd Wright used long, flat Roman bricks and cut limestone wall copings to emphasize the horizontality of the Robie House, built in Chicago in 1906. *(Photo by Mildred Mead. Courtesy of Chicago Historical Society, IChi-14191.)*

FIGURE 8.46
During the second half of the 20th century, Uruguayan engineer Eladio Dieste constructed hundreds of industrial buildings with long-span roof vaults of reinforced clay masonry, using either bricks or, like the example shown here, hollow clay tiles. The span of this roof is about 100 feet (30 m). *Left*, the vaults are long strips with clerestory windows between for daylighting. *Right*, each strip is S-shaped in cross section. This stiffens the vault to prevent buckling and also provides the openings for the windows. *(Photo by Edward Allen.)*

MasterFormat Sections for Brick Masonry

04 05 00	**COMMON WORK RESULTS FOR MASONRY**
05 05 13	Masonry Mortaring
04 05 13.91	Masonry Restoration Mortaring
04 05 16	Masonry Grouting
04 05 19	Masonry Anchorage and Reinforcing
04 21 00	**CLAY UNIT MASONRY**
04 21 13	Brick Masonry
04 54 00	**REFRACTORY BRICK MASONRY**

Key Terms

mason
masonry unit
trowel
mortar
cement–lime mortar
aggregate
portland cement
lime
quicklime
slaked lime, hydrated lime
blended hydraulic cement
masonry cement
air-entraining admixture
mortar cement
mortar type
Type N mortar
Type S mortar
Type O mortar
Type M mortar
workability
proportion specification
property specification
hydraulic cement
lime mortar
nonhydraulic cement
carbonation
hydration
retemper
extended-life admixture
(mortar) admixture
set accelerator
set retarder
integral water repellent
efflorescence
brick
soft mud process
water-struck brick
sand-struck brick, sand-mold brick
dry-press process
stiff mud process
tumbled brick
firing, burning
clamp
clinker brick
periodic kiln
tunnel kiln
water smoking
dehydration
oxidation
vitrification
flashing
fly ash brick
modular brick
modular size
nonmodular size
Utility brick
facing brick, face brick
building brick
solid unit
cored unit
frogged unit
hollow brick
paving brick
firebrick
fireclay
fireclay mortar
brick grade
freeze-thaw weathering
brick type
chippage
stretcher course
rowlock course
soldier course
course
head joint
bed joint
wythe
collar joint
stretcher
header
soldier
rowlock
structural bond
common bond
Flemish bond
English bond
running bond
lead
story pole
line block
lay to the line
tooled joint
weathered joint
vee joint
concave joint
flush joint
raked joint
stripped joint
struck joint
muriatic acid
lintel
corbel
arch
centering
spandrel
gauged brick
rough arch
jack arch, flat arch
barrel vault
dome
buttress
reinforced brick masonry (RBM)
grout
self-consolidating grout
low-lift grouting
high-lift grouting
cleanout hole
tie
quoin
water table

Review Questions

1. How many syllables are in the word "masonry"? (Hint: There cannot be more syllables in a word than there are vowels. Many people, even masons and building professionals, mispronounce this word.)
2. What are the most common types of masonry units?
3. What are the molding processes used in manufacturing bricks? How do they differ from one another?
4. List the functions of mortar.
5. What are the ingredients of mortar? What is the function of each ingredient?
6. Why are mortar joints tooled? Which tooling profiles are suitable for a brick wall in a severe climate?
7. What is the function of a structural brick bond such as common or Flemish bond? Draw the three brick bonds from memory.

Exercises

1. What is the exact height of a brick wall that is 44 courses high when three courses of brick plus their three mortar joints are 8 inches (203.2 mm) high?
2. What are the inside dimensions of a window opening in a wall of modular bricks with ⅜-inch (9.5-mm) mortar joints if the opening is 6 bricks wide and 29 courses high?
3. Obtain sand, hydrated lime, several hundred bricks, and basic bricklaying tools from a masonry supply house. Arrange for a mason to help everyone in your class learn a bit of bricklaying technique. Use lime mortar (hydrated lime, sand, and water), which hardens so slowly that it can be retempered with water and used again and again for many weeks. Lay small walls in several different structural bonds. Make simple wooden centering and construct an arch. Construct a dome about 4 feet (1.2 m) in diameter without using centering, as is done in Figure 8.34. Dismantle what you build at the end of each day, scrape the bricks clean, stack them neatly for reuse, and retemper the mortar with water, covering it with a sheet of plastic to keep it from drying out before it is used again.
4. Design a brick fireplace for a house that you are designing. Select the size and color of brick and the color of mortar. Proportion the fireplace according to the guidelines in Chapter 7. Dimension the fireplace so that it uses only full and half bricks. Draw every brick and every mortar joint in each view of the fireplace. Use rowlocks, soldiers, corbels, and arches as desired for visual effect. How will you span the fireplace opening?

Selected References

Beall, Christine. *Masonry Design and Detailing for Architects, Engineers, and Builders* (6th ed.). New York, McGraw-Hill, 2012.

This 500-page book is an excellent general design reference on brick, stone, and concrete masonry.

Brick Industry Association. *Technical Notes on Brick Construction.* McLean, VA, various dates.

This collection of more than 50 bulletins is available in ring-binder format or as free downloads from the Brick Industry Association's website, www.bia.org. It includes up-to-date information on every aspect of bricks and brick masonry.

Brick Industry Association. *Principles of Brick Masonry.* Reston, VA, 1989.

Despite its age, this 70-page booklet still presents a complete curriculum in the fundamentals of clay masonry construction for the student of building construction.

Hall, William. *Brick.* London, Phaidon Press, 2015.

A visual exploration of brick masonry construction.

Websites

Brick Industry Association: www.bia.org
General Shale Brick: www.generalshale.com
Glen-Gery: www.glengerybrick.com
International Masonry Institute: www.imiweb.org

9

Stone and Concrete Masonry

- **Stone Masonry**
  - Types of Building Stone
  - Quarrying and Milling of Stone
  - Selecting Stone for Buildings
  - Stone Masonry

Sustainability and Stone and Concrete Masonry

- **Concrete Masonry**
  - Manufacture of Concrete Masonry Units
  - Laying Concrete Masonry
  - Dry-Stacked Unit Masonry
  - Decorative Concrete Masonry Units
  - The Economy and Utility of Concrete Masonry Construction
- **Other Types of Masonry Units**
- **Masonry Wall Construction**

Stone offers a wide range of expressive possibilities to the architect. In this detail of a 19th-century church, the columns to the left are made of polished granite and rest on bases of carved limestone. The limestone blocks to the right, squared and dressed by hand, have rough-pointed faces and tooth-axed edges. *(Architect: Cummings and Sears. Photo by Edward Allen.)*

Stone masonry and concrete masonry are similar in concept to brick masonry. Both involve the stacking of masonry units in the same mortar that is used for brick masonry. However, there are important differences: Whereas bricks are molded to shape, building stone must be wrested from quarries in rough blocks, then cut and carved to the shapes desired. We can control the physical and visual properties of bricks to some extent, but we cannot control the properties of stone, so we must learn to select from the bountiful assortment provided by the Earth the type and color that we want and to work with it as nature provides it to us. Concrete masonry units, like bricks, are molded to shape and size, and their properties can be closely controlled. Most concrete masonry units, however, are much larger than bricks, and, like stone, they require slightly different techniques for laying.

Stone Masonry

Types of Building Stone

Building stone is obtained by taking rock from the earth and reducing it to the required shapes and sizes for construction. It is a natural, richly diverse material that can vary greatly in its chemistry, structure, properties, and appearance. Geologically, stone can be classified into three types according to how it was formed:

1. *Igneous rock* was deposited in a molten state.
2. *Sedimentary rock* was deposited by the action of water and wind.
3. *Metamorphic rock* was formerly either igneous or sedimentary rock. Subsequently, its properties were transformed by heat and pressure.

For commercial purposes, ASTM C119 classifies stone used in building construction into six groups: Granite, Limestone, Quartz-Based Stone, Slate, Marble, and Other.

Building stone originates from quarries throughout North America and around the world. Factors that influence the choice of stone source include the stone type, regionally distinctive features, and cost. In the United States, building stone comes from roughly 275 quarries in more than 30 states. Texas, Indiana, Wisconsin, Massachusetts, and Georgia are the largest producer states. But important stone types also come from other areas, such as slate quarried principally in New England and some Middle Atlantic states. The largest importers of stone to the United States are China, Brazil, India, Turkey, and Spain. More than three-quarters of the building stone used in the United States originates in foreign quarries.

Granite Group

Granite is the igneous rock most commonly used for construction in North America. It is a mosaic of mineral crystals, principally feldspar and quartz (silica), and can be obtained in a range of colors that includes gray, black, pink, red, brown, buff, and green. Granite is nonporous, hard, strong, and durable, and is the most nearly permanent of building stones, suitable for use in contact

Figure 9.1
Austin Hall at Harvard University (1881–1884), designed by Henry Hobson Richardson, is a virtuoso performance in stone masonry. Notice the intricate carving of the yellow Ohio sandstone capitals and arch components. The spandrels above the arches are a mosaic of two colors of Longmeadow sandstone blocks. The depth of the arches is intentionally exaggerated to impart a feeling of massiveness to the wall at the entrance to the building. *(Photo by Steve Rosenthal.)*

FIGURE 9.2
The loadbearing walls of the Cistercian Abbey Church in Irving, Texas, are made of 427 rough blocks of limestone from Big Spring, Texas, each 2 × 3 × 6 feet (0.6 × 0.9 × 1.8 m) and weighing about 5000 pounds (2300 kg). The stones were brought directly from the quarry to the site without milling; drill holes are visible in many of the stones. Each stone was bedded in Type S mortar 1 inch (25 mm) thick to allow for irregularities in its horizontal faces. Darker stones are grouped in bands for visual effect. The columns were turned from limestone. Cunningham Architects, designing for a Catholic order that originated 900 years ago in Europe, wanted to build a church that would last for another 900 years. *(Photo by James F. Wilson.)*

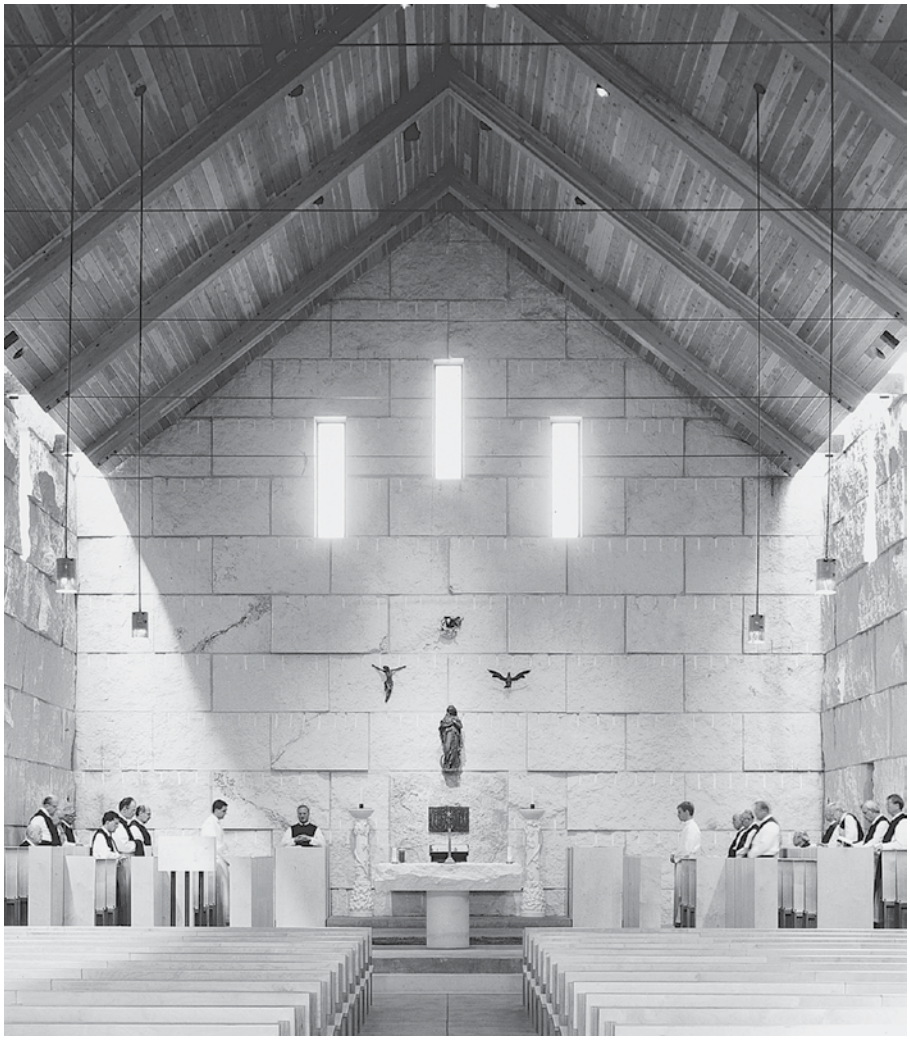


FIGURE 9.3
The heavy timber roof of the Cistercian Abbey Church, flanked by continuous skylights, appears to float above the simple stone volume of the nave. *(Photo by James F. Wilson.)*

with the ground or in locations where it is exposed to severe weathering. Its surface can be finished in any of a number of textures, including a mirror-like polish. Domestic granites are classified according to whether they are fine-grained, medium-grained, or coarse-grained. Requirements for granite dimension stone are defined in ASTM C615.

Basalt, like granite, is a very dense and durable igneous rock. It is usually found only in a dark gray color and is one of a group of stones that may be collectively referred to as "black granites." It is generally used in the form of rubble and is seldom machined.

Limestone Group

Limestone is one of the two principal sedimentary rock types used in construction. It may be found in a strongly stratified form or in deposits that are more homogeneous in structure (*freestone*). Requirements for limestone dimension stone are specified in ASTM C568.

Limestone may be composed either of calcium carbonate (*oolitic limestone*) or of a mixture of calcium and magnesium carbonates (*dolomitic limestone*). Both types were formed long ago from the skeletons or shells of marine organisms. Colors range from almost white through gray and buff to iron oxide red. Limestone is porous and contains considerable groundwater, or *quarry sap*, when quarried. While still saturated with quarry sap, most limestones are easy to work but are susceptible to frost damage. After seasoning in the air to evaporate the quarry sap, the stone becomes harder and resistant to frost damage. Some dense limestones can be polished (and may be classified as marbles), but most are produced with varying degrees of surface texture.

According to ASTM C568, limestones are classified as I Low-Density, II Medium-Density, or III High-Density. Stones in higher density classifications generally are stronger and less porous than those with lower densities. All three classifications are suitable for building applications. The Indiana Limestone Institute classifies limestone into two colors, buff and gray, and four grades. Select grade is the finest-grained and has the fewest natural flaws. Standard and rustic grades are progressively coarser-grained with more natural flaws. The fourth grade, variegated, consists of an unselected mixture of the first three grades.

Quartz-Based Dimension Stone Group

Sandstone is the second major sedimentary rock type used in building construction. Like limestone, it may be found in either a strongly stratified form or as more homogeneous freestone. Sandstone was formed in ancient times from deposits of quartz sand (silicon dioxide). Its color and physical properties vary significantly with the material that cements the sand particles, which may consist of silica, carbonates of lime, or iron oxide. Two of its more familiar forms are *brownstone*, widely used in wall construction, and *bluestone*, a highly stratified, durable stone especially suitable for paving and wall copings. Sandstone will not accept a high polish. Requirements for quartz-based dimension stone are specified in ASTM C616.

Slate Group

Slate is one of the two metamorphic stone groups utilized in building construction. It is formed from clay. It is a dense, hard stone with closely spaced planes of cleavage, along which it is easily split into sheets, making it useful for paving stones, roof shingles, and thin wall facings. It is quarried in a variety of colors, including black, gray, purple, blue, green, and red. Requirements for slate dimension stone are specified in ASTM C629.

Marble Group

Marble is the second of the major metamorphic rock groups. In its true geologic form, it is a recrystallized form of limestone. It is easily carved and polished and occurs in white, black, and nearly every other color, often with beautiful patterns of veining. The properties and appearance of marble vary greatly, depending on the chemistry of the original limestone from which it was formed and, even more so, on the processes by which it was metamorphosed. Requirements for marble dimension stone are specified in ASTM C503.

The Marble Institute of America has established a four-step grading system for marbles, in which Group A includes sound marbles and stone with uniform and favorable working qualities. Groups B through D have progressively less favorable working qualities and more natural faults that may require sticking (cementing together) and waxing (filling of voids with cements, shellac, or other materials). Many of the marbles most prized for their color and figure belong to Group D. The Marble Group also includes other stones that can take a high polish but are not true marbles, such as dense limestones called limestone marble, onyx marble, serpentine marble, and others.

Other Group

The ASTM C119 Other Group includes a variety of less frequently used building stones. *Travertine* is a relatively rare, partially crystallized, and richly patterned calcite (having a chemistry similar to that of limestone) rock deposited by ancient springs. It is marble-like in its physical qualities. Requirements for travertine dimension stone are specified in ASTM C1527. Alabaster, greenstone, schist, serpentine, and soapstone are other stones included in this group.

Quarrying and Milling of Stone

The construction industry uses stone in many different forms. *Fieldstone* is rough building stone obtained from

riverbeds and rock-strewn fields. *Rubble* consists of irregular quarried fragments that have at least one good face to expose in a wall. *Dimension stone* is stone that has been quarried and cut into rectangular shapes; large slabs are often referred to as *cut stone*, and small rectangular blocks are called *ashlar*. *Flagstone* consists of thin slabs of stone, either rectangular or irregular in outline, that are used for flooring and paving. Crushed and broken stone are useful in site work as freely draining fill material, as base layers under concrete slabs and pavings, as surfacing materials, and as aggregates in concrete and asphalt. Stone dust and powder are used in landscaping for walks, drives, and mulch.

The maximum sizes and minimum thicknesses of slabs of cut stone vary from one type of stone to another. Granite, the strongest stone, may be utilized in sheets as thin as ⅜ inch (9.5 mm) in some applications. Marble is generally cut no thinner than ¾ inch (19 mm). However, in most applications, somewhat greater thicknesses than these are advisable. Limestone, the weakest building stone, is rarely cut thinner than 2 inches (51 mm), and 3 inches (76 mm) is the preferred thickness for conventionally set stone. In a 6-inch (152-mm) thickness, limestone may be handled in sheets as large as 5 × 18 feet (1.5 × 5.5 m). Group A marble has a maximum recommended sheet size of 5 × 7 feet (1.5 × 2.1 m).

Dimension stone, whether granite, limestone, sandstone, or marble, is cut from the quarry in blocks. The methods for doing this vary somewhat with the type of stone, and quarrying technology continues to evolve. The most advanced machines for cutting marble and limestone in the quarry are chain saws and belt saws equipped with diamond blades (Figures 9.4 and 9.5). Granite is much harder than other stones, so it is quarried either by drilling and blasting or by the use of a *jet burner* that combusts fuel oil with compressed air. The hot flame at the end of the jet burner lance induces local thermal stress and *spalling* (cracking or flaking of the surface) in the granite. With repeated passes of the lance, the operator gradually excavates a deep, narrow trench to isolate each block of granite from the bedrock. Certain types of granite are quarried successfully with a diamond wire technique, in which a long, taut loop of diamond-studded wire is run at high speed against the stone to make the cut. (See the Chapter 14 sidebar, "Cutting Concrete, Stone, and Masonry," for more information about cutting concrete, stone, and masonry).

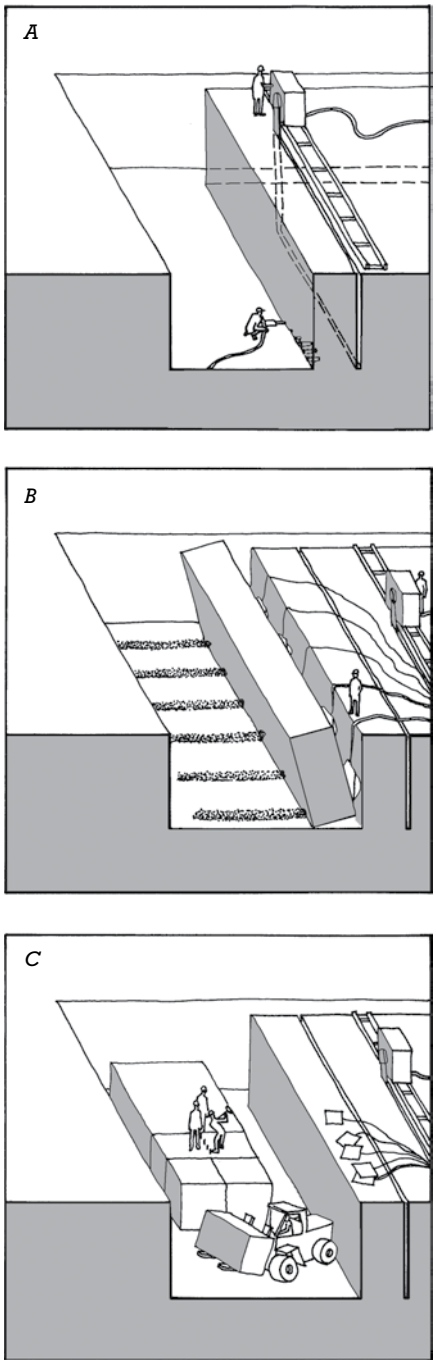


FIGURE 9.4
A typical procedure for quarrying limestone. (*A*) A diamond belt saw divides the limestone bedrock into long cuts, each about 50 feet (15 m) long and 12 feet (3.6 m) high. Multiple horizontal drill holes create a plane of weakness under the outermost cut. (*B*) Rubber air bags are inflated in the saw kerf to "turn the cut," breaking it free of the bedrock and tipping it over onto a prepared bed of stone chips that cushions its fall. (*C*) Quarry workers use sledgehammers to drive steel wedges into shallow drilled holes to split the cut into blocks. A front-end loader removes the blocks and stockpiles them, ready to be trucked to the mill.

(*a*)

(*b*)

FIGURE 9.5

(*a*) The long blade of a diamond belt saw, only the shank of which is visible here, cuts limestone full depth in one pass, using water to lubricate the saw and flush away the stone dust. The saw advances automatically on its portable rails at a maximum rate of about 2½ inches (65 mm) per minute. A chain saw is similar to the belt saw shown here, but it uses a chain of linked, rigid teeth, whereas the belt saw uses a narrow, flexible belt of steel-reinforced polyethylene with diamond cutting segments. (*b*) After the cut has been turned, quarry workers split it into transportable blocks. The man at the top of the photograph is laying out the splitting pattern with a measuring tape and straightedge, working from a list of the sizes of blocks that the mill requires for the specific jobs it is working on. At the right, a worker drills shallow holes in the stone. He is followed by a second worker who places steel wedges in the holes and a third who drives the wedges until the cut splits. Each split takes just several minutes to accomplish.

When preparing cut stone for a building, the stone producer works from the architect's drawings to make a set of shop drawings that show the shape and dimension of each individual stone in the building. After these drawings have been checked by the architect, they are used to guide the work of the mill in producing the stones. Rough blocks of stone are selected in the yard, brought into the mill, and sawed into slabs. The slabs may be sawed into smaller pieces, edged, planed flat or to a molding profile, turned on a lathe, or carved, as required. Automated equipment is often used to cut and carve repetitive pieces. After the desired surface finish has been created, holes for *lewises* and anchors are drilled as needed (Figures 9.6, 9.7, and 9.11). Each finished piece of stone is marked to correspond to its position in the building as indicated on the shop drawings before being shipped to the construction site.

Selecting Stone for Buildings

The selection of building stone is complicated by several factors. Common names for stone do not necessarily correspond to their geologic origins, mineral composition, or physical properties. For example, some stones labeled commercially as marble are devoid of carbonates, the essential mineral group in true marbles, and they differ markedly in their dimensional stability. Commercially applied names for stone often differ regionally as well. In North America, for example, the name "basalt" is applied to a granitelike igneous rock, whereas elsewhere around the globe this term may be used to describe several varieties of sedimentary sandstones or siltstones. Even within one region, the physical characteristics of a particular stone type can vary, sometimes significantly, from one quarry to another, or even within single batches of stone extracted from the same locale.

His powers continually increased, and he invented ways of hauling the stones up to the very top, where the workmen were obliged to stay all day, once they were up there. Filippo had wineshops and eating places arranged in the cupola to save the long trip down at noon. . . . He supervised the making of the bricks, lifting them out of the ovens with his own hands. He examined the stones for flaws and hastily cut model shapes with his pocket knife in a turnip or in wood to direct the men. . . .

—Giorgio Vasari, writing of Filippo Brunelleschi (1377–1446), the architect of the great masonry dome of the Cathedral of Santa Maria del Fiore in Florence, in *The Lives of the Artists*, 1550

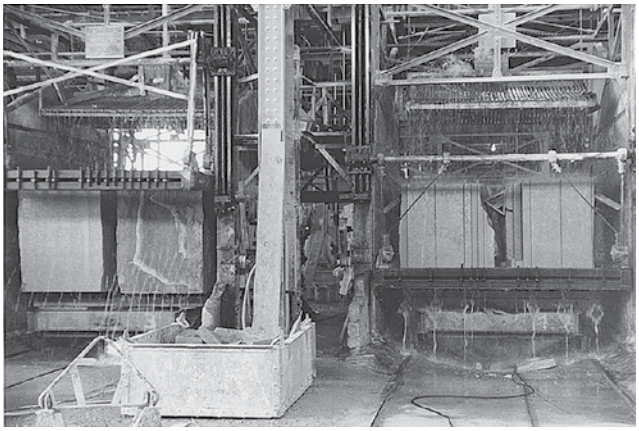
When stone is obtained from an established source, its properties and fitness for use can usually be extrapolated from past experience. When a particular stone has a history of successful performance as exterior cladding, for example, it is generally safe to assume that new supplies of this stone from the same source will continue to be suitable for this type of application. However, when stone comes from an unproven source or will be used in a new way, it should be tested in the laboratory to determine its physical properties and verify its suitability for the proposed use. Stone intended for masonry may undergo *petrographic analysis* (microscopic examination of the stone's mineral content and structure) as well as testing for water absorption, density, compressive strength, dimensional stability, frost resistance, and resistance to attack from salt or other chemicals. Stone panels used as external cladding, as discussed in Chapter 20, may also be tested for bending strength, modulus of rupture, thermal expansion and contraction, and anchor capacity (the load capability of the proposed metal anchor system). Examples of physical property requirements for some common building stone types are listed in Figure 9.8.

The stone industry is international in scope and operation. Architects and building owners have tended to select stone primarily on the basis of appearance, durability, and cost, often with minimal regard to national origin. The most technically advanced machinery for stoneworking, used all over the world, is designed and manufactured in Italy and Germany. A number of Italian companies have earned a reputation for cutting and finishing stone to a very high standard at a reasonable cost. As a result of these factors and the low cost of ocean freight relative to the value of stone, it is possible to choose, for example, a granite that is quarried in Finland, to have the quarry blocks shipped to Italy for cutting and finishing, and to have the finished stone shipped to a North American port, where it is transferred to railcars or trucks for delivery to the building site. Because of the unique character of many domestic stones, both U.S. and Canadian quarries and mills also ship millions of tons of stone to foreign countries each year, in addition to the even larger amount that is quarried, milled, and erected at home.

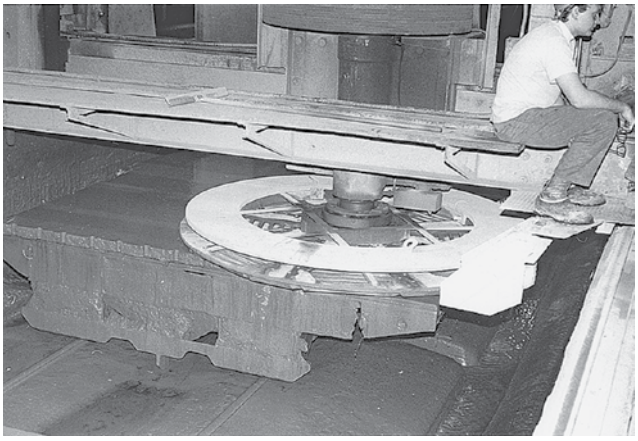
Stone Masonry

Stone is used in two fundamentally different ways in buildings: It may be laid in mortar, much like bricks or concrete blocks, to make walls, arches, and vaults, a method of construction referred to as *stone masonry*. Or it may be mechanically attached to the structural frame or walls of a

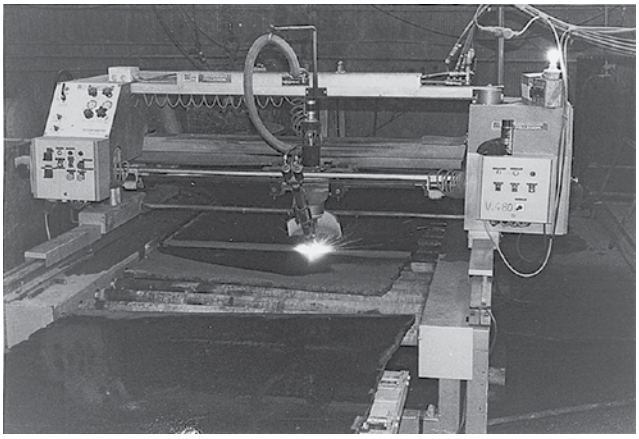
(*a*)



(*b*)

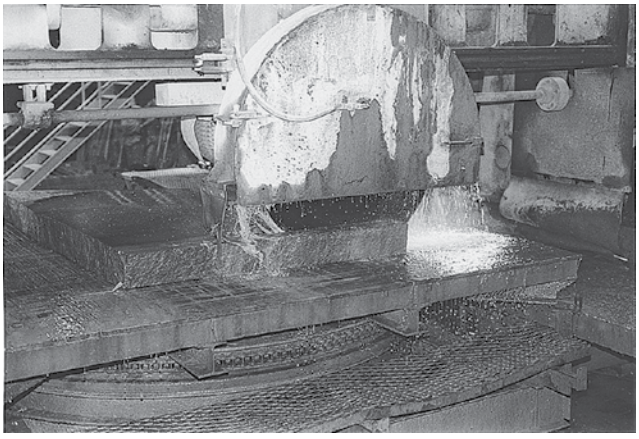


(*c*)



(*d*)

(*e*)

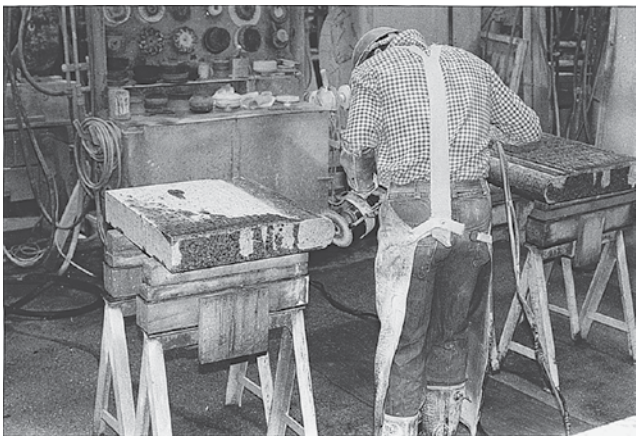


(*f*)

FIGURE 9.6

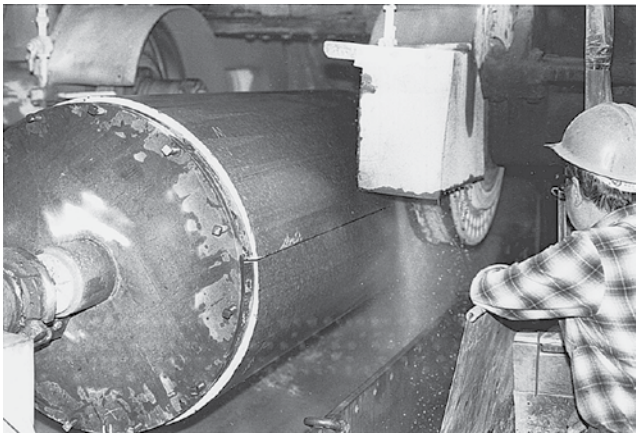
Stone milling operations, showing a composite of techniques for working granite and limestone. (*a*) An overhead crane lifts a rough block of granite from the storage yard to transport it into the plant. The average block in this yard weighs 60 to 80 tons (55 to 75 metric tons). (*b*) Two reciprocating gang saws slice blocks of limestone into slabs. The saw at the right has just completed its cuts, while the one at the left is just beginning. The intervals between the parallel blades are set by the saw operator to produce the desired thicknesses of slabs. Water cools the diamond blades of the saws and flushes away the stone dust. (*c*) A slab of granite is ground to produce a flat surface prior to polishing operations. (*d*) If a textured thermal finish is desired on a granite slab, a propane–oxygen torch is passed across the slab under controlled conditions to cause small chips to explode off the surface. (*e*) A layout specialist, working from shop drawings for a specific building, marks a polished slab of granite for cutting. (*f*) The granite slab is cut into finished pieces with a large diamond circular saw that is capable of cutting 7 feet (2.1 m) per minute at a depth of 3 inches (76 mm).

(*g*)



(*h*)

(*i*)



(*j*)

(*k*)

(*l*)

(*g*) Small pneumatic chisels with carbide-tipped bits are used for special details in granite. (*h*) Hand polishers are used to finish edges of granite that cannot be finished by automatic machinery. (*i*) Cylindrical components of limestone are turned on a lathe. (*j*) A cylindrical column veneer is ground to its true radius. (*k*) Linear shapes of Indiana limestone, a relatively soft stone, can be formed by a profiled silicon carbide blade in a planer. The piece of stone is clamped to the reciprocating bed, which passes it back and forth beneath the blade. The blade's pressure and depth are controlled by the operator's left hand pressing on the wooden lever. Here the planer is making a stepped profile for a cornice. (*l*) Working freehand with a vibrating pneumatic chisel, a carver finishes a column capital of Indiana limestone. Different shapes and sizes of interchangeable chisel bits rest in the curl of the capital. *(Photos* a, c–h, *and* j *courtesy of Cold Spring Granite Co.; photo* i *courtesy Indiana Limestone Institute; photos* b, k, *and* l *by Edward Allen.)*

FIGURE 9.7
This 9-ton (8-metric-ton) Corinthian column capital was carved from a single 30-ton (27-metric-ton) block of Indiana limestone. Rough cutting took 400 hours and carving another 500. Eight of these capitals were manufactured for a new portico on an existing church. *(Architect: I. M. Pei & Partners. Courtesy Indiana Limestone Institute.)*

	Maximum Water Absorption by Weight	Minimum Density	Minimum Compressive Strength	Minimum Modulus of Rupture	Minimum Flexural Strength
Granite ASTM C615	0.40%	160 lb/ft^3 *2560 kg/m^3*	19,000 psi *131 MPa*	1500 psi *10.3 MPa*	1200 psi *8.27 MPa*
Limestone ASTM C568	3–12%	110–160 lb/ft^3 *1760–2560 kg/m^3*	1800–8000 psi *12.4–55.2 MPa*	400–1000 psi *2.76–6.89 MPa*	
Sandstone ASTM C616	1–8%	125–160 lb/ft^3 *2000–2560 kg/m^3*	4000–20,000 psi *27.6–138 MPa*	350–2000 psi *2.41–13.8 MPa*	
Marble ASTM C503	0.20%	144–162 lb/ft^3 *2310–2600 kg/m^3*	7500 psi *51.7 MPa*	1000 psi *6.89 MPa*	1000 psi 6.89 psi

FIGURE 9.8

Minimum property requirements for some common stone types, according to ASTM standards. Moisture absorption is a good indicator of stone durability. The less absorptive the stone, generally the less susceptible it is to freeze-thaw damage or chemical deterioration. Higher moisture levels within stone can also cause accelerated corrosion of metal anchors or reinforcing within the constructed masonry assembly. Stone density is also a good general measure of durability, correlating with higher strength and lower absorption. Compressive strength is especially important for stone used in loadbearing walls. Modulus of rupture is a measure of a stone's resistance to shear and tension forces, a property particularly relevant to the performance of metal anchors used to attach stone to the building. Flexural strength is important in determining the wind load resistance of relatively thin stone panels.

building as a facing, called *stone cladding*. This chapter deals with stone masonry laid in mortar; the detailing and installation of mechanically attached stone cladding are covered in Chapters 20 and 23.

Two simple distinctions are useful in classifying patterns of stone masonry (Figures 9.9 and 9.10):

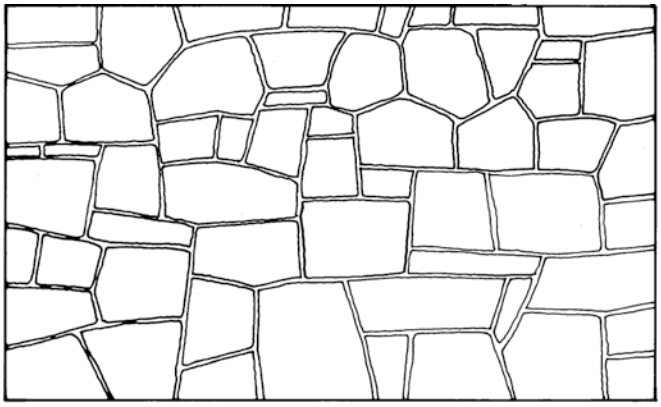
1. Rubble masonry is composed of unsquared pieces of stone, whereas ashlar is made up of squared pieces.
2. *Coursed stone masonry* has continuous horizontal joint lines, whereas *uncoursed* (or *random*) *stone masonry* does not.

Rubble can take many forms, from rounded, river-washed stones to broken pieces from a quarry. It may be either coursed or uncoursed. Ashlar masonry may be coursed or uncoursed and may be made up of blocks that are all the same size or different sizes. The terms are obviously very general in their meaning, and the reader will find some variation in their use even among people experienced in the field of stone masonry.

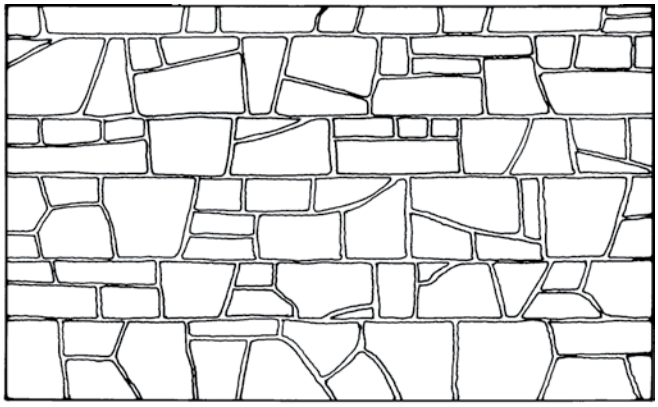
Rubble stonework is laid very much like brickwork, except that the irregular shapes and sizes of the stones require the mason to select each stone carefully to fit the available space and, occasionally, to trim a stone with a mason's hammer or chisel. Ashlar stonework, though also similar in many ways to brickwork, frequently uses stone pieces that are too heavy to lift manually and therefore relies on hoisting equipment to assist the mason in positioning the stones. This, in turn, requires a means of attaching the hoisting ropes to the sides or top of the stone block so as not to interfere with the mortar joint, and several types of devices are commonly used for this purpose (Figure 9.11). Both ashlar and rubble are usually laid with the *quarry bed*, or *grain*, of the stone running in the horizontal direction, because stone is both stronger and more weather-resistant in this orientation.

Stone masonry is frequently combined with concrete masonry to reduce costs. The stone is used where it can be seen, but concrete masonry, which is less expensive, quicker to erect, and more easily reinforced, is used for concealed parts of the wall. One example of such techniques, an exterior *stone veneer* with a concrete masonry backup wall, is illustrated in Figure 9.12.

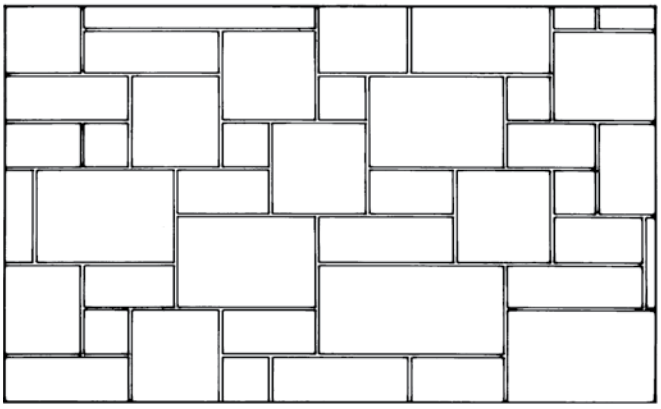
Mortar joints in stone masonry are frequently *raked* (excavated) to a depth ranging from ½ inch to 1 inch (13 to 25 mm) or more after setting of the stones. This prevents uneven settling of stones or spalling of the stone edges that can occur when mortar at the face of the wall dries out and hardens faster than mortar deeper in



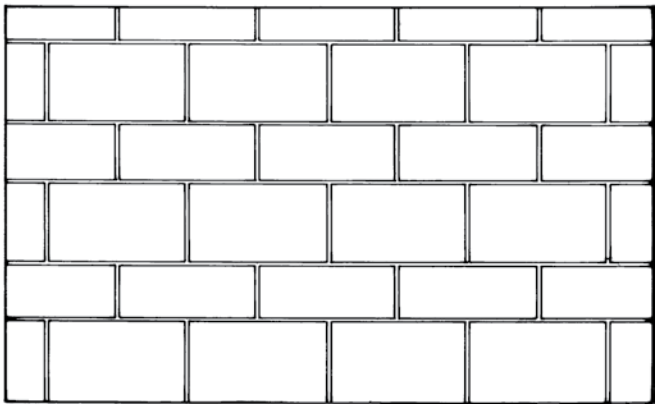
Random Rubble



Coursed Rubble



Random Ashlar



Coursed Ashlar

FIGURE 9.9
Rubble and ashlar stone masonry, coursed and random.

Interactive Exercise

the joint. After the remaining mortar has fully cured, the masons return to *point* the wall by filling the joints out to the face with *pointing mortar* and tooling them to the desired profile. The primary function of the pointing mortar is to form a good weather seal at the face of the stone. For this reason, low-strength mortar with good workability and adhesion characteristics, such as Type O or N mortar, is used. To ensure that the pointing mortar does not itself lead to concentrated stresses and possible spalling at the face of the masonry, it should never be of higher strength than the mortar deeper in the joint. (See Chapter 8 for a discussion of mortar types.) Using pointing mortar also affords the opportunity to use a mortar of different color from the setting mortar. Alternatively, raked joints can be pointed with elastomeric joint sealant. High-quality sealant that does not stain the stone and has the appropriate elastic capabilities should be used. Joint sealant material types and their application are described more fully in Chapter 16.

Some building stones, especially limestone and marble, deteriorate rapidly in the presence of acids. This restricts their outdoor use in regions where the air is heavily polluted, and it also prevents their being cleaned with weak acid, as is often done with bricks. Exceptional care is taken during construction to keep stonework clean: Nonstaining mortars are used, high standards of workmanship are enforced, and the work is kept covered as much as possible. Historically, flashings in stone masonry have been made from durable, noncorroding metals, such as stainless steel, lead, zinc, copper, and lead-coated copper (the lead coating acting to

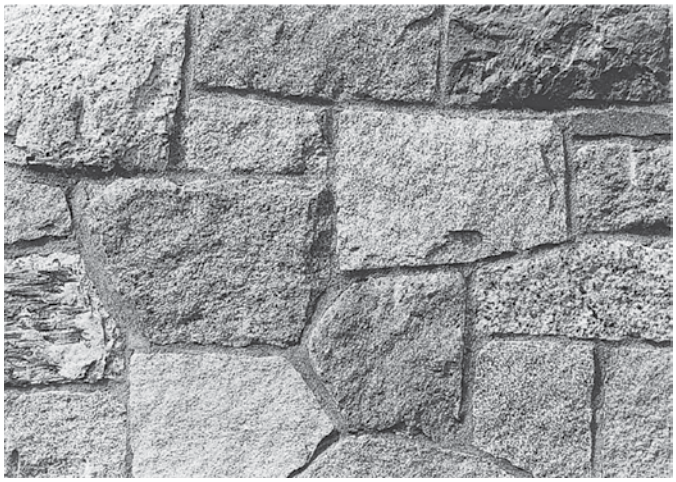
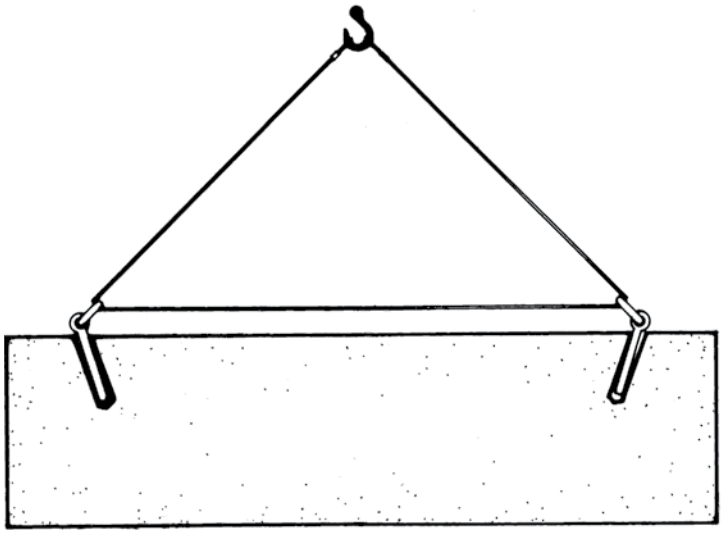
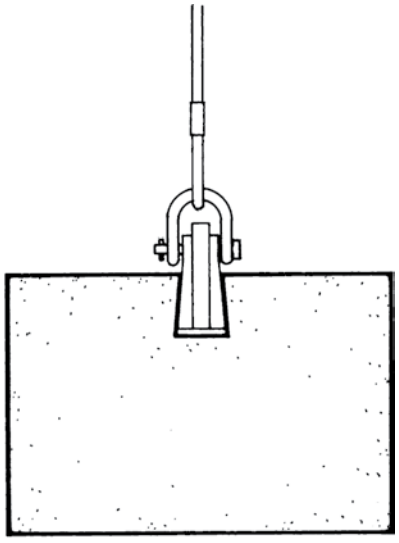


FIGURE 9.10
Random granite rubble masonry (*top*) and random ashlar limestone (*bottom*). *(Photos by Edward Allen.)*



Lewis Pins



Box Lewis

FIGURE 9.11
Lewises permit the lifting and placing of blocks of building stone without interfering with the bed joints of mortar.

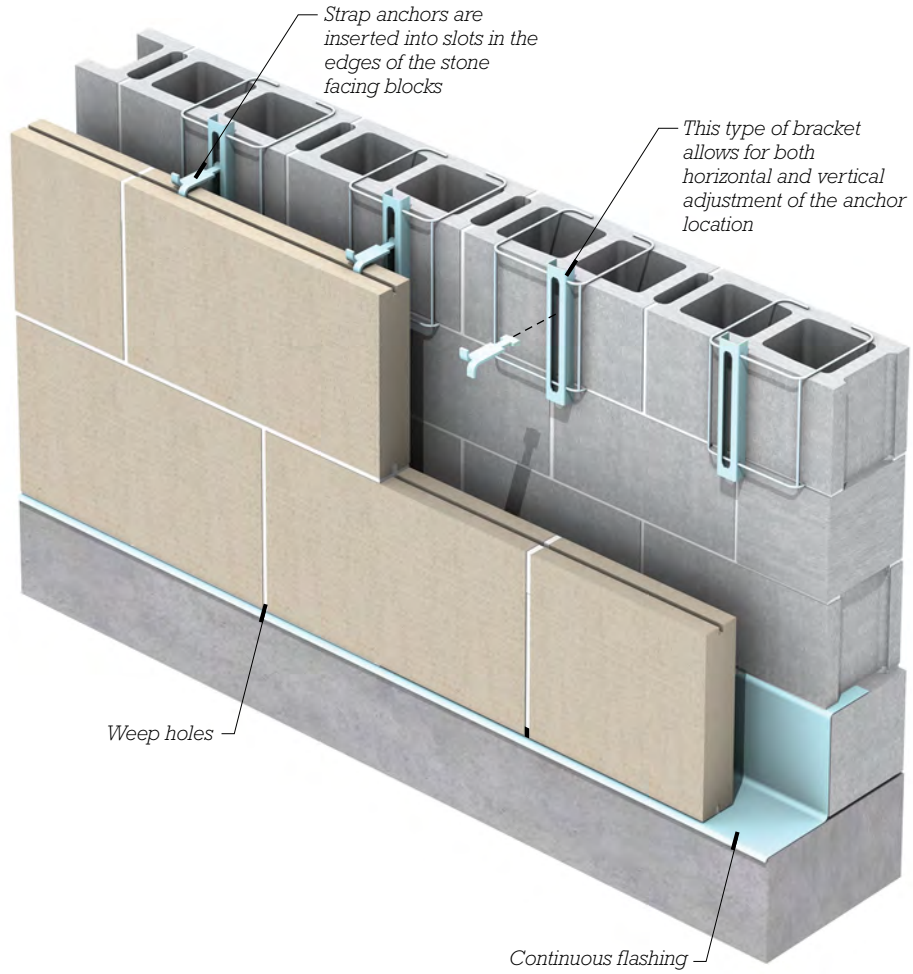


FIGURE 9.12

A conventional method of anchoring blocks of cut-stone facing to a concrete masonry backup wall. The metal strap anchors, which are in direct contact with the stone, should be made of highly corrosion-resistant stainless steel. (When steel corrodes, it expands. Corrosion of the anchors where they engage with the stone could quickly cause damage to the stone itself.) The brackets attached to the concrete masonry backup wall may be stainless steel or less expensive galvanized steel. They are built into the concrete masonry backup wall as it rises. The airspace, or cavity, between the stone and concrete masonry creates a drainage plane that conducts water that penetrates the stone facing to the bottom of the cavity. The waterproof flashing at the base of the cavity forces the water to exit the wall back to the exterior through small drains in the facing called "weep holes." For more information about cavity wall construction, see Chapter 10. For methods of attaching larger panels of stone to a building, see Chapter 20.

prevent staining that can occur with water washing over uncoated copper surfaces). Today, synthetic rubber or bituminous sheet products may also be used, at least where these materials are concealed within the wall and not exposed to view. (Masonry flashings are discussed further in Chapter 10.) Stonework normally may be cleaned only with mild soap, water, and a soft brush.

From thousands of years of experience in building with stone, we have inherited a rich tradition of styles and techniques (Figures 9.13 through 9.17). This tradition is all the richer for its regional variations that are nurtured by the locally abundant stones: warm, creamy Jerusalem limestone in Israel; pristine, white Pentelic marble in Greece; stern gray granite and gray-streaked white Vermont marble in the northeastern United States; joyously colorful marbles and wormy travertine in Italy; golden limestone and gray Aswan granite in Egypt; red and brown sandstones in New York; cool, carvable limestone in France; gray-black basalt and granite in Japan. Though the stone industry is now global in character, its greatest glories are often regional and local.

Sustainability and Stone and Concrete Masonry

Energy Performance

- The thermal mass properties of stone and concrete masonry can help reduce building energy consumption by lessening peak cooling and heating loads or by its use as a component of passive heating and cooling strategies.

Building and Material Life-Cycle Impacts

- A North American manufacturer's EPD reports the following cradle-to-gate impacts for 100 square feet (9.3 m^2) of limestone cladding (including 3⅝-inch (92-mm) thick limestone, mortar, and stone anchors):

Nonrenewable primary energy consumption	9400 MJ (2500 BTU)
Global warming potential	440 kg (970 lb) CO_2 eq.

- The extraction, cutting, shaping, and finishing of 1 cubic foot (0.03 m^3) of stone is estimated to require roughly 120 gallons (450 L) of water that becomes contaminated with stone residue, lubricants, and abrasives. Water filtration and recycling systems can prevent contaminants from entering the wastewater stream and minimize water consumption.
- A manufacturer's EPD reports the following cradle-to-gate impacts for 1 m^3 (35 cu. ft.) of standard 8-inch (200-mm) medium weight concrete masonry units:

Nonrenewable primary energy consumption	2800 MJ (2.7 million BTU)
Global warming potential	400 kg (880 lb) CO_2 eq.
Fresh water consumption	240 L (63 gal)

- Stone and concrete masonry are durable forms of construction that require relatively little maintenance and can last a very long time.
- When a building with stone or concrete masonry is demolished, the stone or masonry units can be crushed and recycled for use as on-site fill or as aggregate for paving. Some building stone can be salvaged for new construction.

Material and Production Attributes

- As much as one-half of quarried stone may become waste during fabrication. Depending on the type of stone, waste may be crushed and used as fill material on construction sites or as aggregate in concrete or asphalt. Stone with a strong color or other unique appearance qualities may be processed into aggregate for use in the manufacture of terrazzo, architectural concrete masonry units, or synthetic stone products. Much stone waste, however, is disposed of as landfill.
- Stone is heavy. It is expensive and energy intensive to transport. Stone may originate from local quarries or from sources in many places around the world. Fabrication may take place close to the source of the stone, close to the building site, or in some other remote location. Where uniquely sourced stones are desired or where specialized fabrication processes or skills are required, shipping over long distances may be required.
- Most concrete masonry units are manufactured in regional plants close to their final end-use destinations.
- Concrete used in the manufacture of masonry units may include recycled materials such as fly ash, crushed glass, slag, and other postindustrial wastes. For more information regarding the sustainability of concrete, see Chapter 13.
- Mortar used for stone and concrete masonry is made from minerals that are generally abundant in the earth. However, portland cement and lime are energy-intensive products to manufacture. For more information about the sustainability of cement production, see Chapter 13.

Unhealthy Materials and Emissions

- Stone and concrete masonry are not normally associated with indoor air quality problems.
- Construction with stone or concrete masonry can reduce reliance on paint finishes, a source of volatile organic compounds.
- Stone and concrete masonry are resistant to moisture damage and mold growth.

Responsible Industry Practices and Social Impacts

- Stone is a plentiful but finite resource. It is usually obtained from open pits, with the attendant disruption of drainage, vegetation, and wildlife habitat.
- Quarry reclamation practices, such as revegetation, land reshaping, and habitat restoration, can mitigate some of the adverse environmental impacts of stone quarrying and convert exhausted quarry sites to other beneficial uses.
- The ANSI/NSC 373: Sustainable Production of Natural Dimension Stone standard provides a framework for certifying sustainable and responsible industry practices among stone producers.

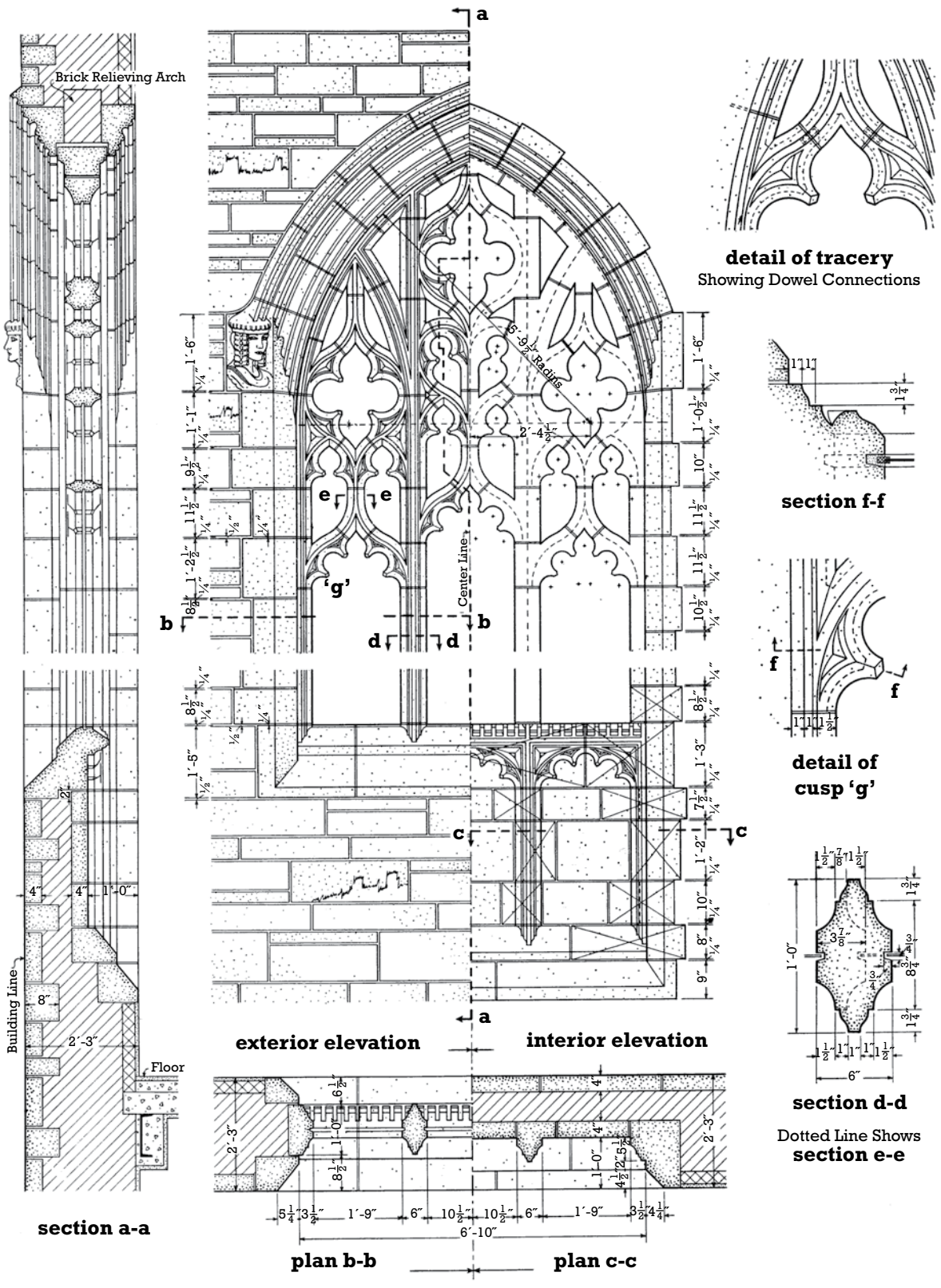


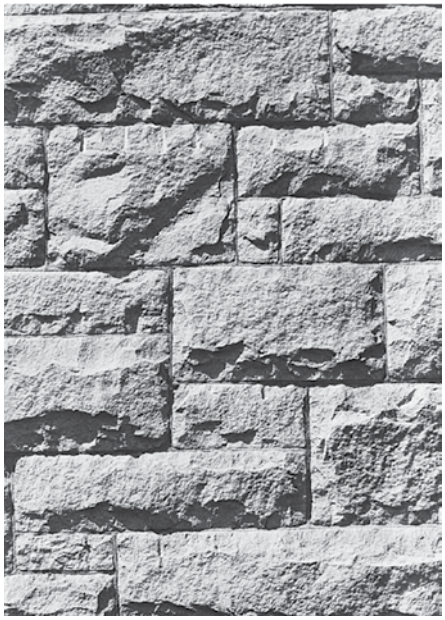
FIGURE 9.13

Details of Gothic window framing and tracery in limestone. In the lower portion of section *a-a*, note the 8-inch-deep facing stones that act as bonding units with the interior masonry wythes. This type of composite construction is discussed further in Chapter 10. *(Courtesy Indiana Limestone Institute.)*

Figure 9.14
Columns of igneous red porphyry and basalt, Basilica de La Sagrada Familía, Barcelona, by architect Antoni Gaudí. *(Photo by Joseph Iano.)*

Figure 9.15
The Marshall Field Wholesale Store, built in 1885 in Chicago, rested on a two-story base of red granite. Its upper walls were built of red sandstone, and its interior was framed with heavy timber. *(Architect: H. H. Richardson. Photo by John McCarthy. Courtesy of Chicago Historical Society, IChi-01688.)*

Figure 9.16
The Suzallo Library, University of Washington, built in 1926, combines richly detailed limestone, brick, and terra cotta in its ornate exterior walls. *(Photo by Joseph Iano.)*



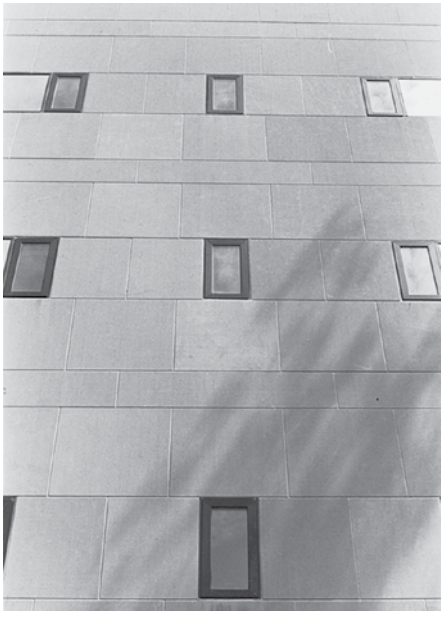
(*a*)

(*b*)

(*c*)

(*d*)

(*e*)



(*f*)

FIGURE 9.17

Cut-stone detailing. (*a*) Random ashlar of broken face granite on H. H. Richardson's Trinity Church in Boston (1872–1877) still shows the drill holes of its quarrying. (*b*) Dressed stonework in and around a window of the same church contrasts with the rough ashlar of the wall. (*c*) Stonework on a 19th-century apartment building grows more refined as it distances itself from the ground and meets the brick walls above. (*d*) The base of the Boston Public Library (1888–1895; McKim, Mead and White, architect) is constructed of pink granite, with strongly rusticated blocks between the windows. (*e*) A college chapel is simply detailed in limestone. (*f*) A contemporary college library is clad in bands of limestone. *(Architect: Shepley Bulfinch Richardson & Abbott. Photos by Edward Allen.)*

Concrete Masonry

Concrete masonry units (CMUs) are manufactured in three basic forms: larger hollow units that are commonly referred to as *concrete blocks*, solid bricks, and, less commonly, larger solid units.

Manufacture of Concrete Masonry Units

Concrete masonry units are manufactured by vibrating a stiff concrete mixture into metal molds, then immediately turning out the wet blocks or bricks onto a rack so that the mold can be reused at the rate of 1000 or more units per hour. The racks of concrete masonry units are cured at an accelerated rate by subjecting them to steam, either at atmospheric pressure or, for faster curing, at higher pressure (Figure 9.18). After steam curing, the units are bundled on wooden pallets for shipping to the construction site.

Concrete masonry units are made in a variety of sizes and shapes (Figures 9.19 and 9.20). They are also made with different densities of concrete, some of which use cinders, pumice, blast furnace slag, or expanded lightweight aggregates rather than crushed stone or gravel. Many colors and surface textures are available. Special shapes are relatively easy to produce if a sufficient number of units will be produced to amortize the expense of the mold. The major ASTM standards under which concrete masonry units are manufactured are C90 for loadbearing units, C129 for nonloadbearing units, and C55 for concrete bricks.

ASTM C90 establishes three weights of loadbearing concrete masonry units, as shown in Figure 9.21. Although all three weight classifications require the same minimum compressive strength, heavier blocks are denser and typically have greater compressive strength than lighter blocks. Heavier blocks are also less expensive to manufacture,

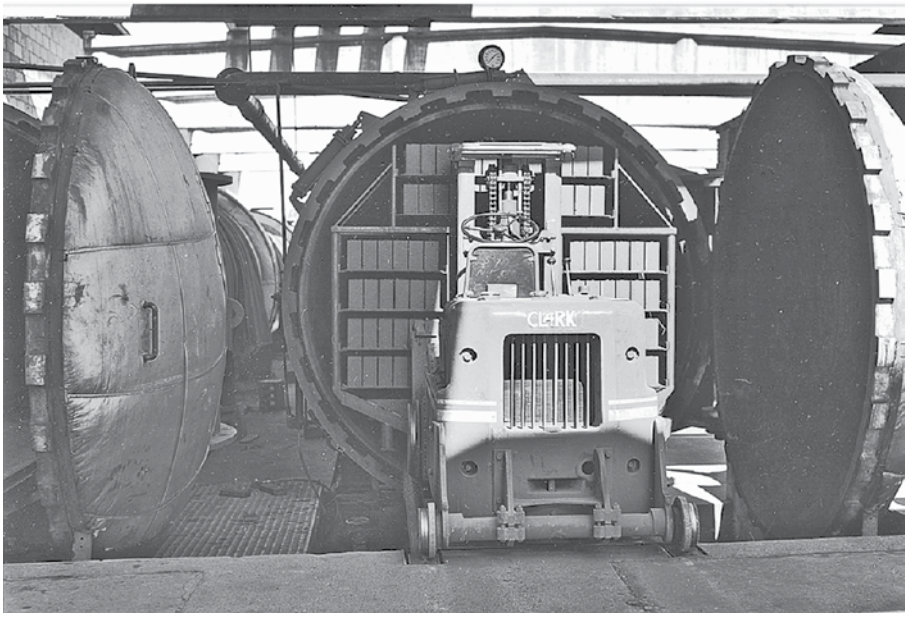


Figure 9.18
A forklift truck loads newly molded concrete masonry units into an autoclave for steam curing. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photos from Portland Cement Association, Skokie, IL.)*

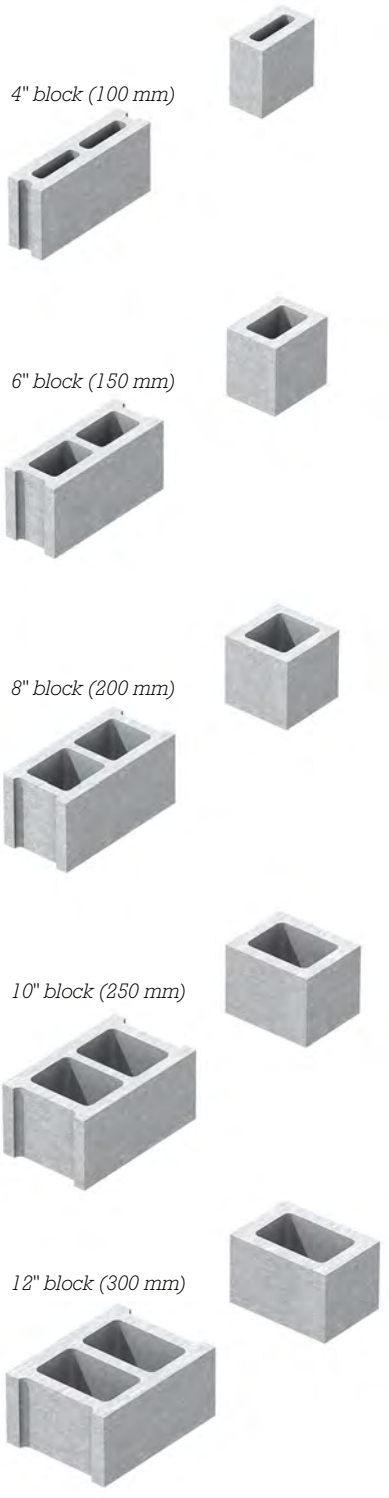


Figure 9.19
American standard concrete blocks and half-blocks. Each full block is nominally 8 inches (200 mm) high and 16 inches (400 mm) long.

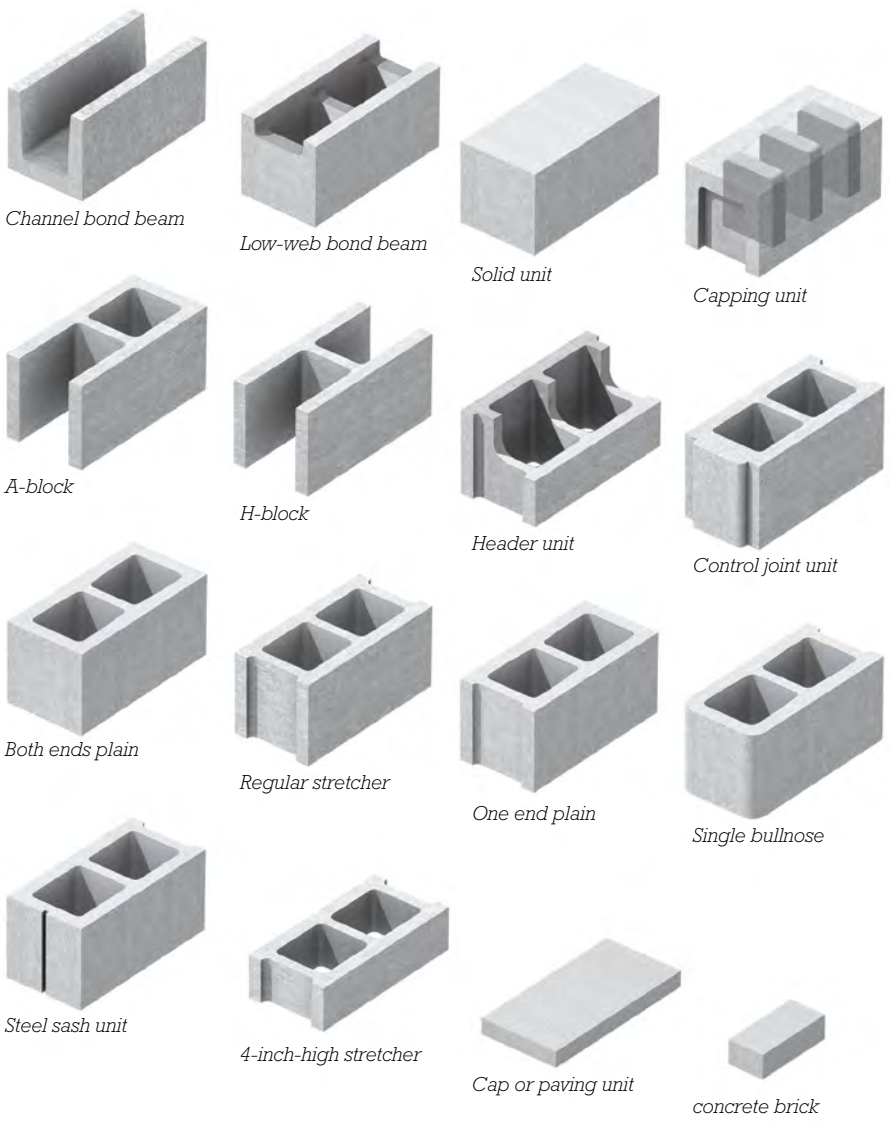


FIGURE 9.20
Other concrete masonry shapes. Concrete bricks are interchangeable with modular clay bricks. Header units accept the tails of a course of headers from a brick facing. The use of control joint units is illustrated in Figure 10.19. Bond beam units have space for horizontal reinforcing bars and grout and are used to tie a wall together horizontally. They are also used for reinforced block lintels. A-blocks are used to build walls with vertical reinforcing bars grouted into the cores in situations where there is insufficient space to lift the blocks over the tops of the projecting bars; one such situation is a concrete masonry backup wall that is built within the frame of a building, as seen in Figure 20.1.

ASTM C90 Weight Classification	Density of Concrete (dry)	Typical Weights of Individual Units
Normal weight (sometimes also referred to as heavyweight)	125 pcf (2000 kg/m^3) or more	33–39 lb (15–18 kg)
Medium weight	From 105 pcf to less than 125 pcf (1680–2000 kg/m^3)	28–32 lb (13–15 kg)
Lightweight	Less than 105 pcf (1680 kg/m^3)	20–27 lb (9–12 kg)

FIGURE 9.21
Specified densities and typical weights of hollow concrete masonry units. Note the possibly confusing naming of Normal and Medium weight blocks: Normal weight blocks are heavier than Medium weight.

FIGURE 9.22
Concrete blocks and bricks can be cut very accurately with a water-cooled, diamond-bladed saw. For rougher sorts of cuts, a few skillful blows from the mason's hammer will suffice. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photos from Portland Cement Association, Skokie, IL.)*

absorb moisture less readily, have better resistance to sound transmission, and are more resistant to abuse. But their greater weight also makes heavier blocks more expensive to ship and more labor intensive and expensive for masons to lay in comparison to lighter-weight blocks. The greater density of heavier blocks also gives them lower thermal resistance and lower fire resistance. Choice of concrete masonry unit weight also varies with regional differences in availability and local construction trade preferences.

Although innumerable special sizes, shapes, and patterns are available, the dimensions of American concrete masonry units are based on an 8-inch (203-mm) cubic module. The most common block is nominally 8 × 8 × 16 inches (203 × 203 × 406 mm). The actual size of the block is 7⅝ × 7⅝ × 15⅝ inches (194 × 194 × 397 mm), which allows for a mortar joint ⅜ inch (9 mm) thick. This standard block is designed to be lifted and laid conveniently with two hands (compared to a brick, which is laid with one). Its double-cube proportions work well for running bond stretchers, for headers, and for corners.

Although concrete masonry units can be cut with a diamond-bladed power saw (Figure 9.22), it is more economical and produces better results if the designer lays out buildings of concrete masonry in dimensional units that correspond to the module of the block (Figure 9.23). Nominal 4-inch, 6-inch, and 12-inch (102-mm, 152-mm, and 305-mm) block thicknesses are also common, as is a solid concrete brick that is identical in size and proportion to a modular clay brick. A handy feature of the standard 8-inch (203-mm) block height is that it corresponds exactly to three courses of ordinary clay or concrete brickwork, or two courses of oversize bricks, making it easy to interweave blockwork and brickwork in composite walls.

Laying Concrete Masonry

The accompanying photographic sequence (Figure 9.24) illustrates the technique for laying concrete block

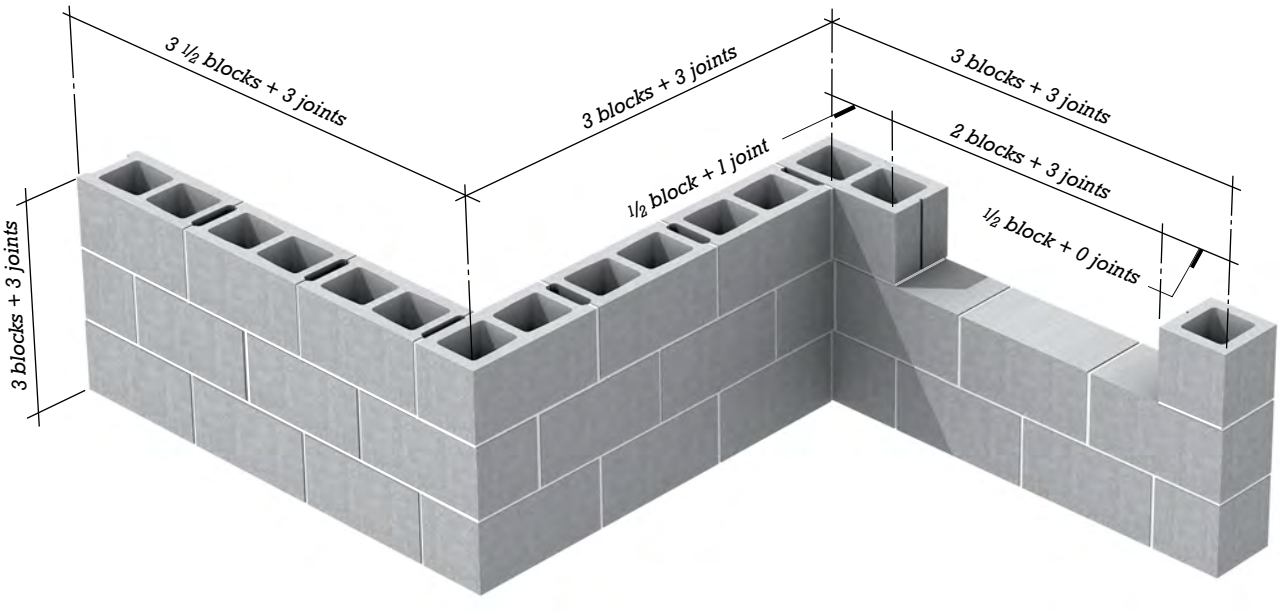


FIGURE 9.23
Modular dimensioning of concrete masonry construction. Concrete masonry buildings should be dimensioned to use uncut blocks except under special circumstances.

Interactive Exercise

(*a*)

(*b*)

(*c*)

(*d*)

FIGURE 9.24

Laying a concrete masonry wall. (*a*) A bed of mortar is spread on the footing. (*b*) The first course of blocks for a lead is laid in the mortar. Mortar for the head joint is applied to the end of each block with the trowel before the block is laid. (*c*) The lead is built higher. Mortar is normally applied only to the face shells of the block and not to the webs. (*d*) As each new course is started on the lead, its height is meticulously checked with either a folding rule or, as shown here, a story pole marked with the height of each course.

(*continued*)

(*e*)

(*f*)

(*g*)

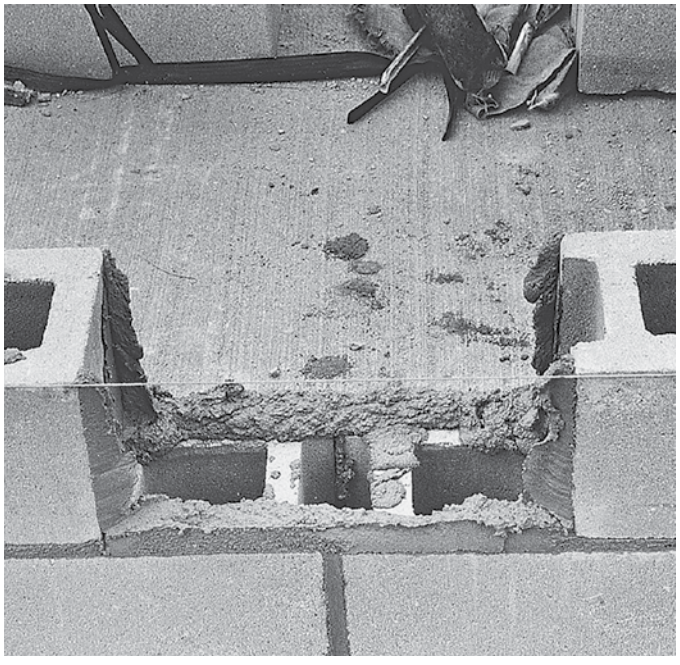
(*h*)

FIGURE 9.24 *continued*

(*e*, *f*) Each new course is also checked with a spirit level to be sure that it is level and plumb. Time expended in making sure that the leads are accurate is amply repaid in the accuracy of the wall and the speed with which blocks can be laid between the leads. (*g*) The joints of the lead are tooled to a concave profile. (*h*) A soft brush removes mortar crumbs after tooling.

(*i*)

(*j*)



(*k*)

(*l*)

(*i*) A mason's line is stretched taut between the leads on line blocks. (*j*) The courses of blocks between the leads are laid rapidly by aligning each block with the stretched line; no story pole or spirit level is necessary. The mason has laid bed joint mortar and "buttered" the head joints for a number of blocks. (*k*) The last block to be installed in each course of infill blocks, the closer, must be inserted between blocks that have already been laid. The bed and head joints of the already laid blocks are buttered. (*l*) Both ends of the closer blocks are also buttered with mortar, and the block is lowered carefully into position. Some touching up of the head joint mortar is often necessary. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photos from Portland Cement Association, Skokie, IL.)*

walls. The mortar is identical to that used in brick walls, but in most walls only the face shells of the block are mortared, with the webs left unsupported (Figure 9.24*c, j,* and *k*).

Concrete masonry is frequently reinforced with steel to increase its loadbearing capacity, or resistance to seismic forces and cracking. *Horizontal reinforcing* may take the form of *joint reinforcing*, welded grids of small-diameter steel rods that are laid into the bed joints at set vertical intervals (Figure 9.25). For greater strength, bond beam blocks (Figure 9.20) or special blocks with channeled webs (Figure 9.26) allow heavier reinforcing bars to be placed horizontally. The horizontal bars may be embedded in grout before the next course of masonry is laid. In this case, the grout is confined within the cores of the reinforced course by a strip of metal mesh laid in the bed joint beneath the course. Or, the bars may be grouted later, at the same time as grouting for vertical bars.

Vertical block cores are easily reinforced by inserting bars and grouting, using either the low-lift or high-lift technique, as described in Chapter 8. In most cases only those cores that contain reinforcing bars are grouted, but sometimes, for added strength, all the vertical cores are filled, whether or not they contain reinforcing (Figure 9.27).

Lintels for concrete block walls may be made of steel angles, combinations of rolled steel shapes, reinforced concrete, or bond beam blocks with grouted horizontal reinforcing (Figure 9.28).

Dry-Stacked Unit Masonry

Dry-stacked and *surface-bonded* masonry walls are constructed by stacking concrete masonry units in a running bond directly upon one another without the application of mortar. Where leveling is required, metal or high-density plastic shims are used. Once the wall stack is complete, a thin layer of a special cement plaster containing short reinforcing fibers of alkali-resistant glass is applied to each side. After the plaster coating has cured, this surface coating joins the blocks securely to one another both in tension and compression. The plaster coating also serves as a finish with an appearance resembling stucco. Surface-bonded masonry unit construction and materials are governed by ASTM C946. It can be performed with relatively unskilled labor, making it an attractive alternative for low-rise masonry construction where skilled masonry trades are not readily available.

Decorative Concrete Masonry Units

Decorative (or *architectural*) *concrete masonry units* are easily and economically manufactured in an unending variety of surface patterns, textures, and colors intended for exposed use in exterior and interior walls.

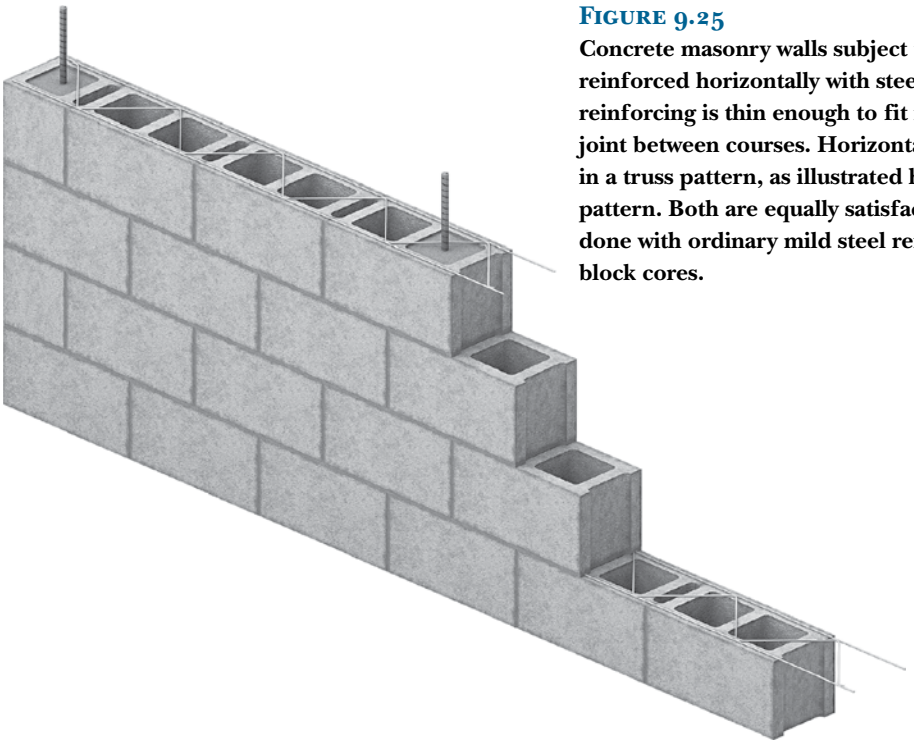


FIGURE 9.25
Concrete masonry walls subject to only moderate stresses are reinforced horizontally with steel joint reinforcing. This type of reinforcing is thin enough to fit into the ordinary mortar bed joint between courses. Horizontal joint reinforcing is available in a truss pattern, as illustrated here, or in a rectilinear ladder pattern. Both are equally satisfactory. Vertical reinforcing is done with ordinary mild steel reinforcing bars grouted into block cores.

FIGURE 9.28
(*Opposite page*) Lintels for openings in concrete masonry walls. At the top, a steel lintel for a broad opening is made up of a wide-flange section welded to a plate. Steel angle lintels are used for narrower openings. In the middle, a reinforced block lintel is composed of bond beam units. At the bottom, a precast reinforced concrete lintel is seen.

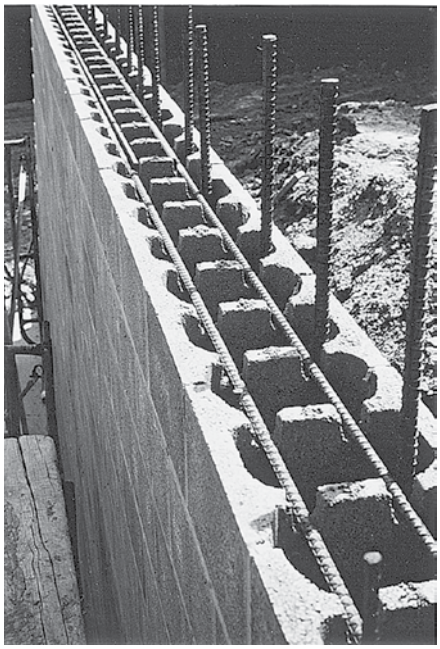


FIGURE 9.26
These specially formed masonry units are grooved to allow the insertion of horizontal reinforcing bars. The course of block will then be grouted to embed the bars. *(Courtesy of G. R. Ivany and Associates, Inc.)*

FIGURE 9.27
Grout is deposited in the cores of a reinforced concrete masonry wall using a grout pump and hose. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photos from Portland Cement Association, Skokie, IL.)*

FIGURE 9.29
A small house by architects W. G. Clark and Charles Menefee is simply detailed in concrete masonry. A reinforced masonry retaining wall helps to link the building visually to the site. *(Photo by Jim Rounsevell.)*

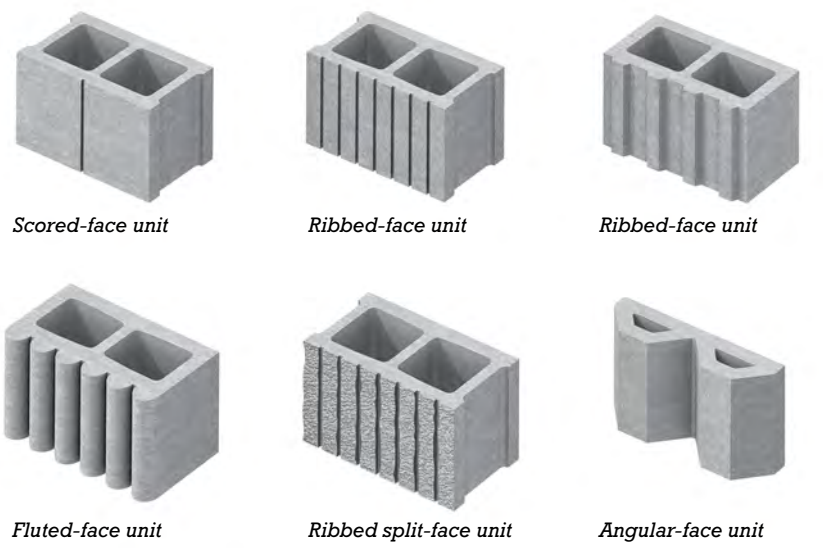


FIGURE 9.30
Some decorative concrete masonry units, representative of literally hundreds of designs currently in production. The scored-face unit, if the slot in the face is filled with mortar and tooled, produces a wall that looks as if it were made entirely of half-blocks. The ribbed split-face unit is produced by casting "Siamese twin" blocks that are joined at the ribs, then shearing them apart.

FIGURE 9.31
A facade of split-face concrete masonry. *(Architect: Paderewski Dean Albrecht & Stevenson. Courtesy of National Concrete Masonry Association.)*

A few such units are diagrammed in Figure 9.30, and some of the resulting surface textures are depicted in Figures 9.31 and 9.32. Mold costs for producing special units are low when spread across the number of units required for a medium- to large-sized building. Many of the textured concrete masonry units that are now considered standard originated as special designs created by architects for particular buildings.

The Economy and Utility of Concrete Masonry Construction

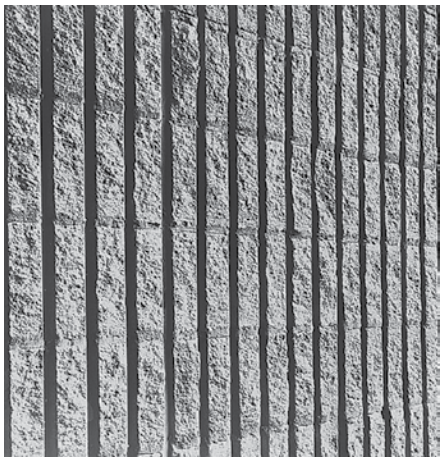
Concrete masonry is a versatile building material, and walls built from it are usually more economical than comparable ones made of brick or stone. The concrete blocks themselves are cheaper on a volumetric basis and are made into a wall much more quickly because of their larger size (a single standard concrete block occupies the same volume as 12 modular bricks). Concrete blocks can be produced to required degrees of strength, and because their hollow cores allow for the easy insertion of reinforcing steel and grout, they are widely used in bearing wall construction. Billions of concrete blocks are manufactured annually in North America alone.

However, concrete masonry is relatively porous, and single-wythe exterior concrete masonry walls are prone to leaking when exposed to heavy rains. Except in dry climates, such walls must be protected with exterior coatings or integral water repellents. For this reason, concrete masonry in exterior wall construction is more often used as the backup wythe in a cavity wall with brick or stone facing, as described in Chapter 10.

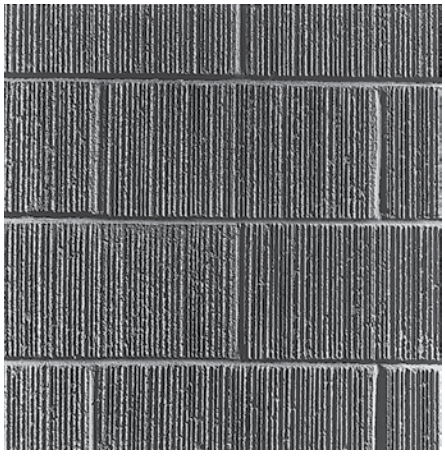
(*a*)

(*b*)

(*c*)



(*d*)



(*e*)

FIGURE 9.32
Some walls of decorative concrete masonry. (*a*) Split block. (*b*) Slump block, which is molded from relatively wet concrete and allowed to sag slightly after molding and before curing. (*c*) Split blocks of varying sizes laid in a random ashlar pattern. (*d*) Ribbed split-face blocks. (*e*) Striated blocks. *(Courtesy of National Concrete Masonry Association.)*

Other Types of Masonry Units

Bricks, stones, and concrete blocks are the most commonly used types of masonry units. In the past, hollow tiles of cast gypsum or fired clay were often used for partition construction (Figure 23.33). Both have been supplanted in the United States by concrete blocks, though hollow clay tiles are still widely used in other parts of the world. *Structural glazed facing tiles* of clay remain in use, especially for partitions, where their durable, easily cleaned surfaces are advantageous, as in public corridors, toilet rooms, institutional kitchens, locker and shower rooms, and industrial plants (Figure 23.34).

Structural terra cotta—glazed or unglazed molded decorative units of fired clay—was widely used until the mid-20th century and is often seen on the facades of late-19th-century masonry buildings in the United States (Figure 8.43). Terra cotta had almost disappeared from the U.S. market a few decades ago, but restoration work on older buildings created a demand for it and generated a renewed desire to use it in new buildings, rescuing the last manufacturers from the brink of obsolescence. Today, terra-cotta masonry, in both historical and contemporary shapes, is readily available.

Glass blocks can be made from glass that is clear, heat-absorbing, or reflective, with many surface patterns and in a variety of colors (Figure 9.33). Unlike brick, concrete masonry, and stone, glass blocks are nonabsorbent. When glass masonry walls are constructed, the mortar stiffens more slowly than it does with these other materials, so temporary spacers are inserted between units to maintain proper spacing until the mortar hardens.

Autoclaved aerated concrete (AAC) is made from sand, lime, water, and a small amount of aluminum powder. These materials are reacted with steam to produce a relatively lightweight, aerated concrete that consists primarily of calcium silicate hydrates.

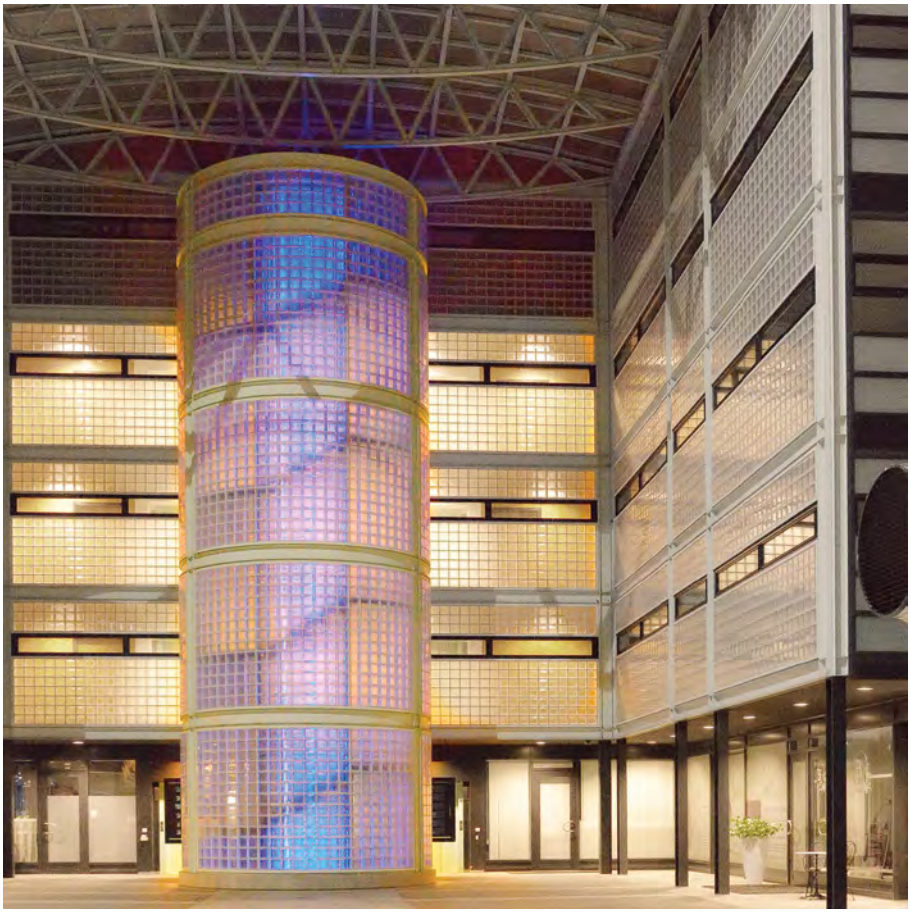


Figure 9.33
Glass block stairway enclosure and exterior window wall. *(Photo by Joseph Iano.)*

AAC is available in solid blocks that are laid in mortar like other concrete masonry units. It is also made into unreinforced wall panels and steel-reinforced lintels and floor/ceiling panels. Because of its trapped gas bubbles, which are created by the reaction of the aluminum powder with the lime, the density of AAC is similar to that of wood, and it is easily sawed, drilled, and shaped. It has moderately good thermal insulating properties. It is not nearly as strong as normal-density concrete, but it is sufficiently strong to serve in loadbearing walls, floors, and roofs in low-rise construction. Walls of AAC are too porous to be left exposed; they are usually stuccoed on the exterior and plastered on the interior.

Masonry Wall Construction

Bricks, stones, and CMUs are mixed and matched in both loadbearing and nonloadbearing walls of many types. The more important of these wall constructions are presented in the next chapter.

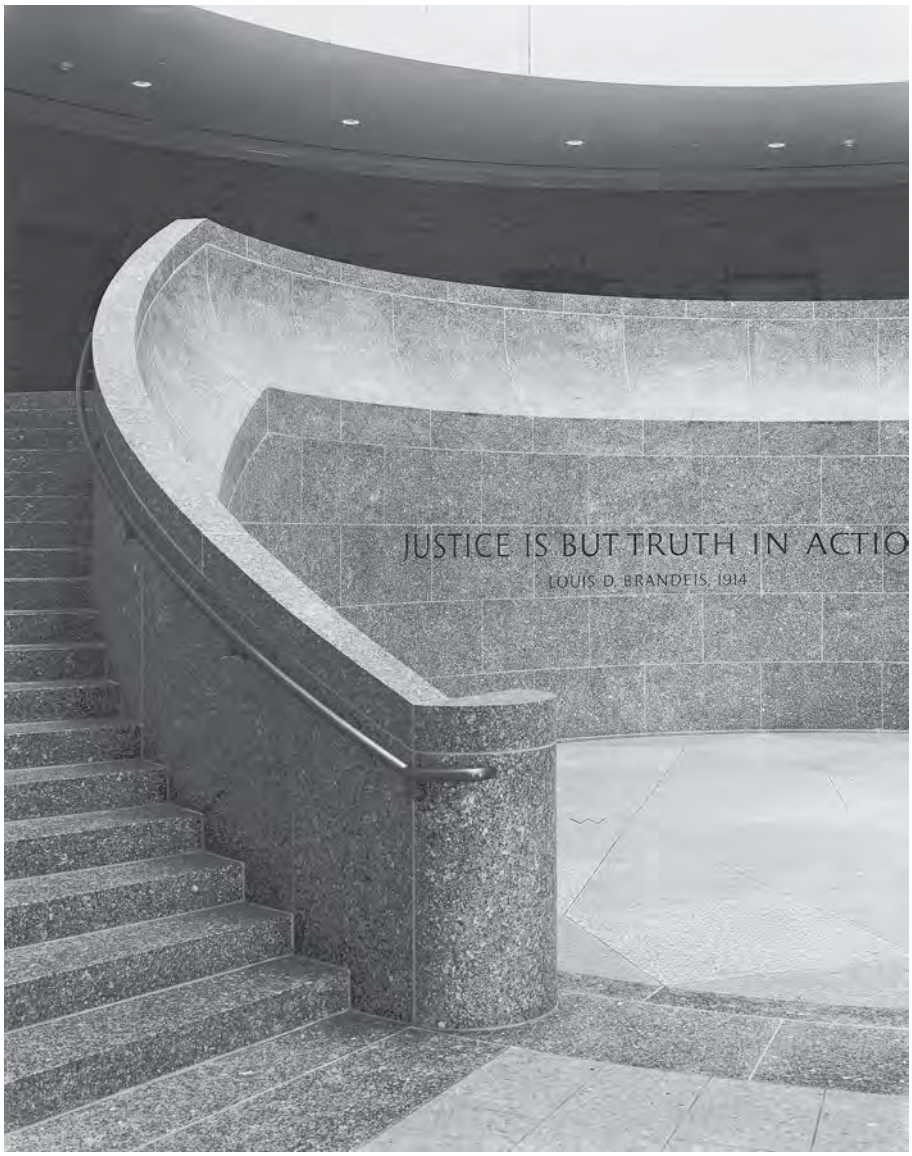


Figure 9.34
Dark granite, simply and beautifully detailed, creates a feeling of quiet dignity for the main stair of the Moakley Federal Courthouse in Boston. The floor is made of terrazzo with matching and contrasting colors of stone chips. *(Photo © Steve Rosenthal.)*

MasterFormat Sections for Stone and Concrete Masonry

04 05 00	**COMMON WORK RESULTS FOR MASONRY**
04 05 16	Masonry Grouting
04 05 19	Masonry Anchorage and Reinforcing
04 21 00	**CLAY UNIT MASONRY**
04 21 26	Glazed Structural Clay Tile Masonry
04 21 29	Terra Cotta Masonry
04 22 00	**CONCRETE UNIT MASONRY**
04 22 00.16	Surface-Bonded Concrete Unit Masonry
04 22 23	Architectural Concrete Unit Masonry
04 22 26	Autoclaved Aerated Concrete Unit Masonry
04 23 00	**GLASS UNIT MASONRY**
04 43 00	**STONE MASONRY**
04 43 13	Stone Masonry Veneer
04 43 16	Stone Fabrications

Key Terms

building stone
igneous rock
sedimentary rock
metamorphic rock
granite
basalt
limestone
freestone
oolitic limestone
dolomitic limestone
quarry sap
sandstone
brownstone
bluestone
slate
marble
travertine
fieldstone
rubble
dimension stone
cut stone
ashlar
flagstone
jet burner
spalling
lewis
petrographic analysis
stone masonry
stone cladding
coursed stone masonry
uncoursed stone masonry, random stone masonry
quarry bed, grain
stone veneer
raked mortar joint
pointed mortar joint
pointing mortar
concrete masonry unit (CMU)
concrete block
horizontal reinforcing
joint reinforcing
dry-stacked concrete masonry
surface-bonded concrete masonry
decorative concrete masonry unit, architectural concrete masonry unit
structural glazed facing tile
structural terra cotta
glass block
autoclaved aerated concrete (AAC)

Review Questions

1. What are the major types of stone used in construction? How do their properties differ?
2. What sequence of operations would be used to produce rectangular slabs of polished marble from a large quarry block?
3. In what ways is the laying of stone masonry different from the laying of bricks?
4. What are the advantages of concrete masonry units over other types of masonry units?
5. How long is a wall that is made up of 22 concrete masonry units, each nominally 8 × 8 × 16 inches (203 × 203 × 406 mm), joined with ⅜-inch (10-mm) mortar joints?
6. How may horizontal and vertical steel reinforcement be introduced into a CMU wall?

Exercises

1. Design a stone masonry facade for a downtown bank building that is 32 feet (9.8 m) wide and two stories high. Draw all the joints between stones on the elevation. Draw a detail section to show how the stones are attached to a concrete masonry backup wall.

2. Design a masonry gateway for one of the entrances to a college campus with which you are familiar. Choose whatever type of masonry you feel is appropriate, and make the fullest possible use of the decorative and structural potentials of the material. Show as much detail of the masonry on your drawings as you can.

3. Visit a masonry supply company and view all the types of concrete masonry units that are available. What is the function of each?

4. Design a simple concrete masonry house that a student could build for his or her own use, keeping the floor area to 400 square feet (37 m^2).

5. Design a decorative CMU that could be used to build a richly textured wall.

Selected References

Indiana Limestone Institute of America. *ILI Handbook*. Bedford, IN, updated regularly.

This is the definitive reference on the use of limestone in building. It includes the history and provenance of Indiana limestone, recommended standards and details for its use, and architectural case histories. Available as a free download from the Institute's website, iliai.com.

Marble Institute of America. *Dimensional Stone Design Manual*. Cleveland, OH, updated regularly.

Standards, specifications, and details for dimensional stonework are included in this volume. Though all stone types are included, the emphasis is on marble. Available in hard copy or as a free download from the Natural Stone Institute's website, www.naturalstoneinstitute.org.

National Concrete Masonry Association. *Annotated Design and Construction Details for Concrete Masonry*. Herndon, VA, 2003.

A treasury of typical concrete masonry details.

National Concrete Masonry Association. *TEK Manual for Concrete Masonry Design and Construction*. Herndon, VA, updated regularly.

This comprehensive collection of technical bulletins covers every major aspect of concrete masonry products and design. The complete TEK bulletin series is also available free online from NCMA member websites, such as www.ncma-br.org/e-tek-nbs.asp.

Panarese, W., S. Kosmatka, and F. Randall. *Concrete Masonry Handbook for Architects, Engineers, and Builders (6th ed.)*. Skokie, IL, Portland Cement Association, 2008.

This is a clearly written guide to every aspect of concrete masonry.

Websites

Bybee Stone Company: www.bybeestone.com

Capitol Concrete Products, Technical Aid: www.capitolconcreteproducts.com/Technicalaid.html

Echelon Masonry: www.echelonmasonry.com

Indiana Limestone Institute: www.iliai.com

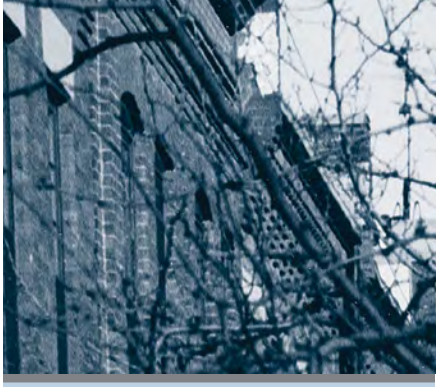
National Concrete Masonry Association: ncma.org

Natural Stone Council: naturalstonecouncil.org

Natural Stone Institute: www.naturalstoneinstitute.org

Portland Cement Association: www.cement.org

BICYCLES
SNOWBOARDS



10

Masonry Wall Construction

- **Types of Masonry Walls**
  - Composite Masonry Walls
  - Masonry Cavity Walls
  - Masonry Loadbearing Walls

  Preliminary Design of Loadbearing Masonry Structures
- **Spanning Systems for Masonry Bearing Wall Construction**
  - Masonry and Wood Light Frame Construction
  - Masonry and Heavy Timber Construction
  - Steel and Concrete Decks with Masonry Bearing Walls
- **Detailing Masonry Walls**
  - Cavity Drainage and Flashings
  - Thermal Insulation
- **Special Problems of Masonry Construction**
  - Expansion and Contraction

  Movement Joints in Buildings
  - Efflorescence
  - Mortar Joint Deterioration
  - Moisture Resistance of Masonry
  - Cold- and Hot-Weather Construction
- **Masonry Paving**
- **Masonry and the Building Codes**
- **Uniqueness of Masonry**

America's rich fabric of 19th-century downtown buildings is made up largely of buildings whose construction was traditionally referred to as Ordinary construction: exterior masonry loadbearing walls with floors and roof spanned by light wood joists. Today, this method of building is defined in the International Building Code as Type III construction. *(Photo by Edward Allen.)*

The world's most enduring buildings are constructed of masonry. Such buildings' thick, monolithic walls can stand for centuries, their great mass providing strength, durability, and moderation of the flow of heat and moisture between indoors and outdoors. Traditional masonry construction methods survive to the present day in such buildings as the Washington National Cathedral (Washington, DC), constructed primarily of solid limestone masonry. However, most contemporary construction combines the essential materials of masonry—brick, stone, concrete block, and mortar—with more modern materials and technological innovations to create walls that are thinner, lighter in weight, stronger, faster to erect, and better able to control the flow of heat and moisture through the wall.

Types of Masonry Walls

Composite Masonry Walls

Composite masonry walls are solid walls in which multiple wythes are bonded in such a way that they act as a unified mass. In traditional examples of this wall type, different masonry materials are used in different parts of the wall to achieve an optimum balance between appearance, longevity, and economy. For example, face units of terra cotta, stone, or facing brick, chosen for their appearance and durability, may be combined with interior wythes of more utilitarian materials such as building brick or hollow clay tile. The wall's outer wythes are bonded to the interior with some combination of header units and metal anchors (Figure 10.1*A*). In contemporary construction, composite walls may be constructed of mixed masonry types or of all one type (Figure 10.1*B*). Header units are rare, and bonding of wythes is typically accomplished with steel ties and reinforcing. Especially when a composite masonry wall is loadbearing, it is most common to construct the wall of all one masonry unit type to best balance the structural behavior between wythes.

Masonry Cavity Walls

Every masonry wall is porous to some degree. Solid masonry construction relies on the wall's mass to absorb

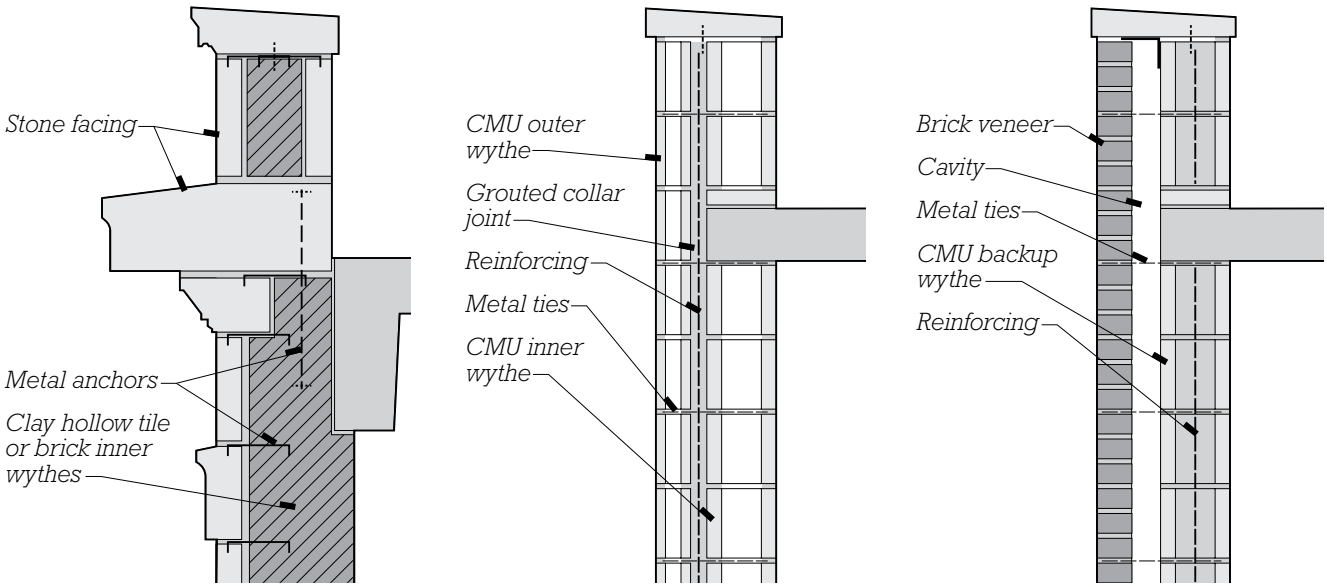


Figure 10.1

Types of masonry walls. *(A)* In a traditional composite wall, the inner parts of the wall are constructed of less expensive masonry materials while the exposed parts are faced with more durable and attractive materials. *(B)* In this contemporary composite wall, concrete masonry is used throughout. The wall acts as a unified structural mass and gravity loads are resisted by both wythes. *(C)* In cavity wall construction, a vertical hollow space separates the outer wythe, or veneer, from the backup wythe. The effects of moisture exposure and exterior temperature changes are mostly confined to the outer wythe. Gravity loads are usually resisted solely by the backup wythe. In all three diagrams, roofing, flashings, air and moisture barriers, and interior finishes have been omitted for clarity.

and then gradually release moisture that enters the wall. A *cavity wall* interposes a hollow vertical space within the wall to intercept water that penetrates the outer wythe (Figure 10.1*C*). Only masonry ties, made of corrosion-resistant galvanized or stainless steel, span the cavity and connect the face wythe, or *veneer*, to the backup wythes (Figures 10.2 and 10.3). When water penetrates the veneer and reaches the cavity, it has no place to go but down. At the bottom of the cavity, water is caught by a thin, impervious membrane called a *flashing* and drained through *weep holes* back to the exterior (Figure 10.4).

To further protect against water penetration, *dampproofing* or other water-resistive material is applied to the cavity side of the backup wythe of the wall. Any water that bridges the cavity is thus discouraged from penetrating further toward the interior. This material can, optionally, also act as an air barrier, controlling air leakage through the wall. To control the flow of heat through the wall, insulating boards of rigid foam plastic or mineral fiber may be inserted into the cavity (Figure 10.3*d–f*). A cavity wall is an example of drained cladding, a type of exterior wall construction discussed in more detail in Chapter 16.

During construction, the cavity must be kept free of mortar droppings, brick chips, and other debris, which can clog the weep holes or form bridges that transport water across the cavity. This requires good construction practices and careful inspection. When a masonry unit is pushed into position in a bed joint of mortar, some mortar is squeezed out of the joint on each side. Normally, the mason cuts off this extruded mortar with a trowel and returns it to the mortar pan, but inevitably some of the mortar falls into the cavity. Eventually, enough mortar may accumulate at the bottom of the cavity to block drainage holes.

One solution to this problem is to place a strip of wood on the steel ties in the cavity to catch such mortar droppings, then to pull out this strip and scrape the mortar off before placing the next row of ties. However, this method is an added inconvenience for the mason and is prone to spilling mortar as the wood strip is lifted from the cavity. An alternative is for the mason to bevel the bed joint with the trowel, making it thinner at the cavity face and thicker at the outside face, before placing the masonry units. This minimizes the squeezing-out of mortar into the cavity. As a last defense against blocked cavity drainage, *mortar deflection material*, in the form of various free-draining woven or matted products, may be used. This material is inserted either at the bottom of the cavity or continuously throughout the cavity's full height, acting to catch mortar droppings so that cavity bottom remains unclogged (Figure 10.5).

In a loadbearing cavity wall, the backup wythe normally carries structural loads, while the outer wythe serves as a nonstructural veneer. In nonloadbearing cavity walls, the backup wythe does not carry gravity loads (other than its own weight) but still provides lateral support to the veneer through the metal ties, anchoring the veneer in place and bracing it against wind and seismic forces. Additional examples of cavity wall construction can be found elsewhere in this text: A brick veneer curtain wall with concrete masonry backup is illustrated in Figures 20.1 through 20.3; a brick veneer with a steel stud backup wall is shown in Figure 20.5 and in Figure C in the "Case Study: Seattle University Law School" at the end of Chapter 20; a brick veneer with wood light framing is illustrated in Figure 6.35; and an illustration of exterior stone facing and cavity wall is shown in Figure 9.12.

Masonry Loadbearing Walls

Walls constructed of brick, stone, or concrete masonry can be used to support roof and floor structures of virtually any material. Because these *masonry loadbearing walls* (or more simply, *masonry bearing walls*) can perform double duty as both structural frame and enclosure, they remain economically competitive with other systems, such as wood, steel, or concrete, that require separate systems to fill in between loadbearing parts. Figure 10.6 lists common ranges of compressive strengths and densities for concrete masonry, bricks, and various types of stone used in bearing wall construction. In practice, the working stresses are significantly lower than the ultimate strengths listed in the table, accounting for the lower strength of the mortar between units and to provide appropriate factors of safety.

Reinforced Masonry Walls

Loadbearing masonry walls may be built with or without reinforcing. However, unreinforced masonry walls are not as strong and are particularly vulnerable to lateral forces from earthquake, heavy winds, or earth pressures (when used below grade). In the past, unreinforced walls were used in North America to support buildings as tall as 16 stories (Figure 8.37). Today, however, virtually all loadbearing masonry construction is reinforced with steel or other materials that add tensile strength and ductility. Reinforced masonry loadbearing walls can also be constructed to be thinner than comparable unreinforced walls, resulting (especially in taller buildings) in savings in materials, construction labor, and floor area taken up by the wall.

The engineering design of masonry loadbearing walls is governed by a standard jointly prepared by the American Concrete Institute, the American Society of Civil Engineers, and The Masonry Society, and published as *Building Code Requirements for Masonry Structures, ACI 530/ASCE 5/TMS 402*. This document establishes engineering procedures for the strength and stiffness of

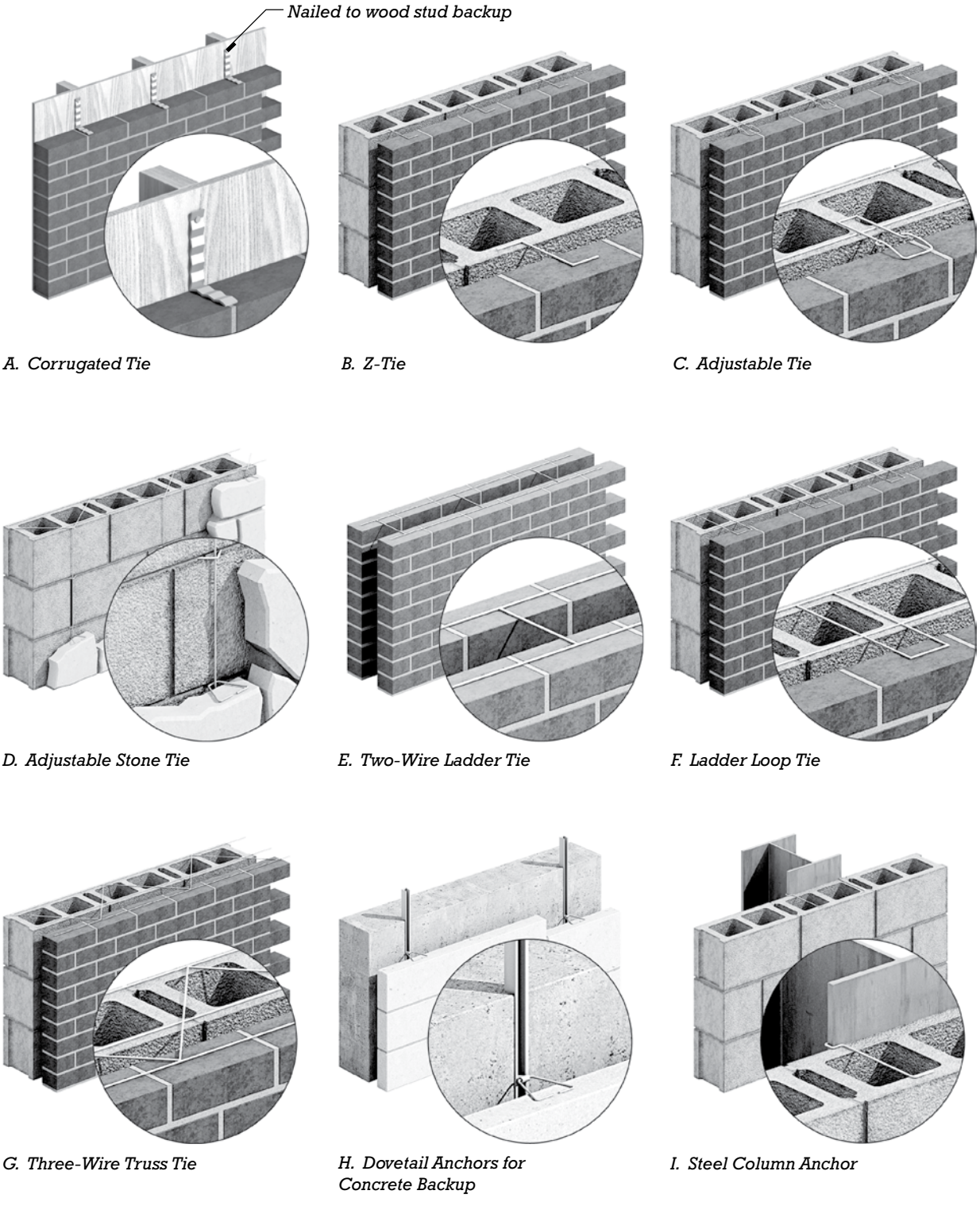
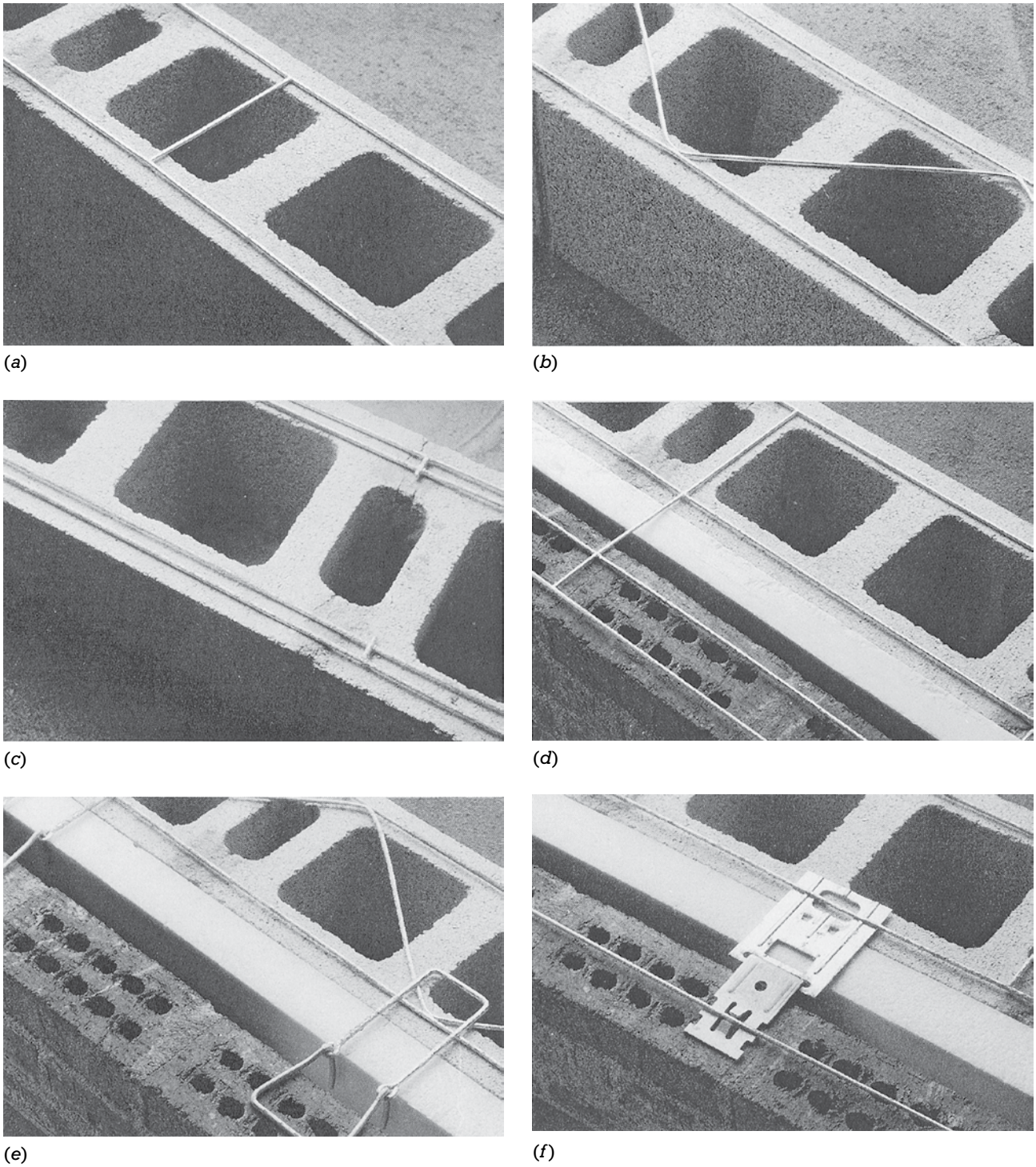


FIGURE 10.2

Masonry ties and joint reinforcing. These are only a few examples from among dozens of types available. Corrugated ties (*A*) have little strength or stiffness and are recommended only for anchoring low-rise veneer to wood-framed backup walls. Z-ties (*B*) are stiffer than corrugated ties. Adjustable ties (*C*) accommodate irregularities in course height between wythes. Adjustable stone ties (*D*) have excessive play, unless the collar joint is filled with mortar. The ladder and truss ties (*E–G*) combine horizontal joint reinforcement with the masonry tie. Truss-type horizontal reinforcing (*G*) can develop composite action between wythes, resulting in a stiffer wall. It is suitable for solid walls but should not be used with cavity walls, where differential rates of expansion and contraction between the wythes can lead to bowing of the wall. (Cavity wall construction is illustrated in these examples. In the case of composite construction, the space between wythes would be filled with mortar.)



(*a*) (*b*) (*c*) (*d*) (*e*) (*f*)

FIGURE 10.3

Photographs of joint reinforcing and ties. (*a*) Ladder reinforcing for a single wythe of concrete masonry. (*b*) Truss reinforcing. (*c*) The double rods of seismic ladder reinforcing offer greater strength than the single rods of normal ladder reinforcing. (*d*) Ladder-type side rod reinforcing reaches across an insulated cavity to reinforce the face wythe of brick masonry and tie it to the backup wythe of concrete masonry. (*e*) Truss-type eye-and-pintle tie reinforcing allows for some adjustment in course heights. (*f*) Ladder-type seismic tab tie reinforcing allows the construction of the face wythe to lag behind that of the concrete masonry backup wythe and still provides reinforcement and positive tying of the face wythe to the backup. *(Courtesy of Dur-O-Wal, Inc.)*

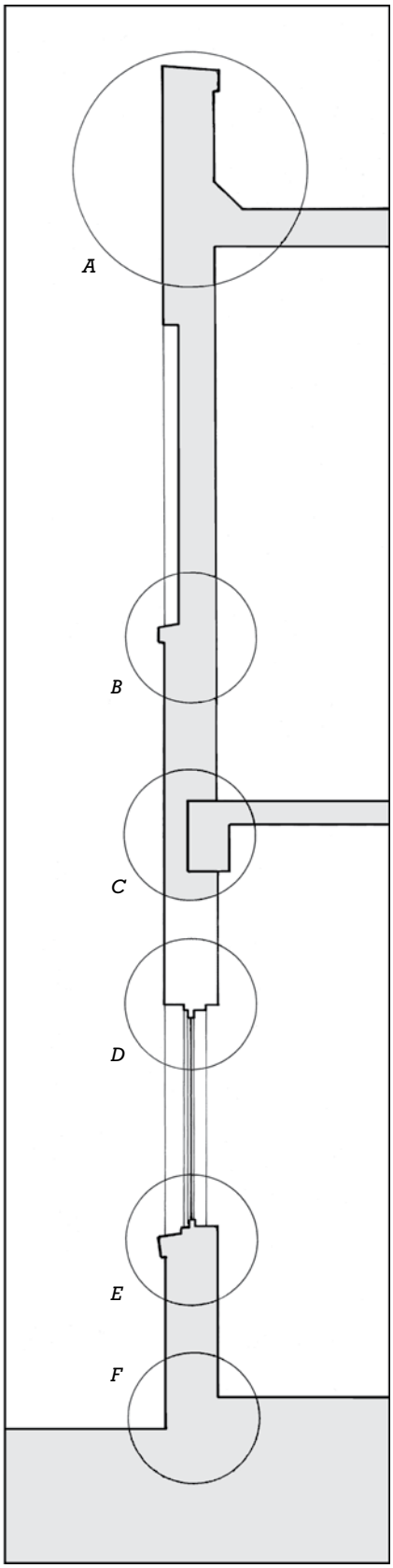
loadbearing walls, materials requirements for masonry units, reinforcing, mortar, and grout, and appropriate methods of construction. Methods of reinforcing brick and concrete masonry walls have been described in Chapters 8 and 9 and are further illustrated throughout this chapter.

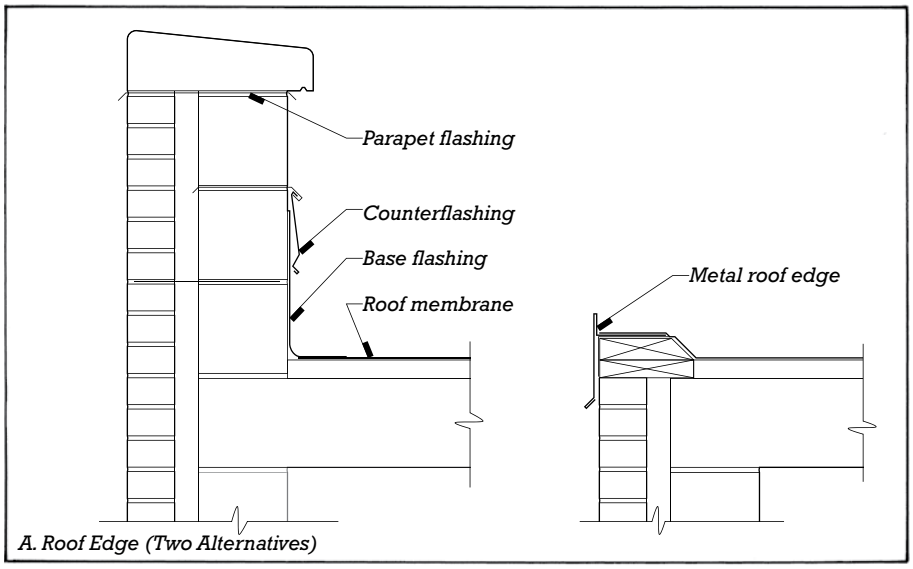
Posttensioned Masonry Walls

Masonry walls may be posttensioned utilizing high-strength steel threaded rods or flexible tendons rather than ordinary, untensioned vertical reinforcing bars (Figure 10.7). The posttensioning elements are anchored into the foundation and run vertically through the masonry wall, either between wythes or in the cores of the masonry units. After the wall has been completed and the mortar has cured, each rod or tendon is tensioned (stretched very tightly) and anchored in its taut condition to a horizontal steel plate at the top of the wall. Threaded rods are tensioned by tightening a nut against the steel plate at the top of the wall. Tendons are stretched by a special hydraulic jack and then anchored with the aid of a steel chuck that grips the wires of the tendon. In either case, the tensioning places the wall under a vertical compressive prestress that is considerably higher than would be created by the weights of the masonry and the floors and roofs that it supports. The effect is to strengthen the wall against forces that would normally induce tension in the wall, such as those from wind or seismic loads. This allows the use of thinner walls with fewer grouted cores, saving material and labor. The concept of posttensioning is discussed and illustrated in more detail in Chapter 13.

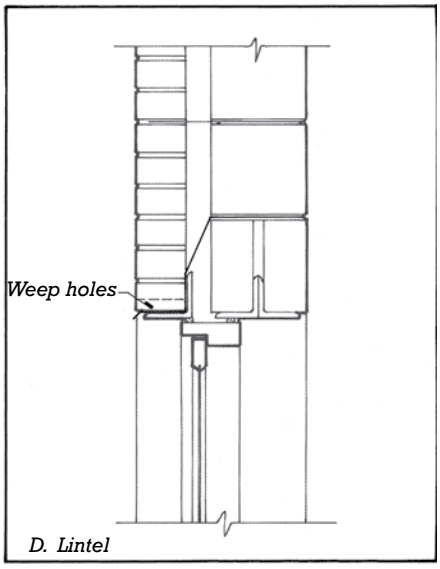
FIGURE 10.4

Masonry wall flashings. The letters on the full-height section on this page refer to the larger-scale details on the opposite page. The flashing shown for a recess or projection in *B* is for a composite masonry wall. All other details illustrate cavity wall construction. The *reglet* shown in the right-hand shelf angle detail in *C* is a continuous slot cast into the face of the concrete into which the top edge of the flashing is inserted. The end dam shown in the center drawing prevents water trapped by the flashing from spilling off the flashing ends rather than out through the weep holes.

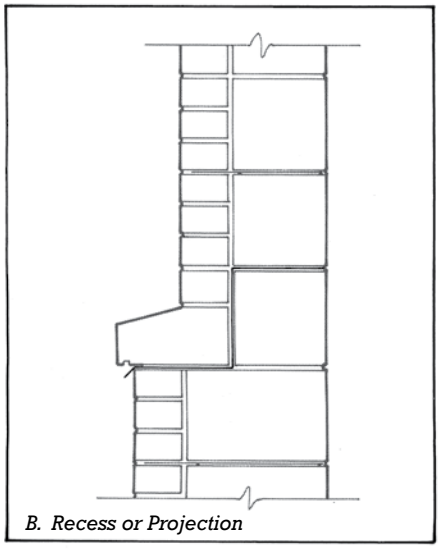




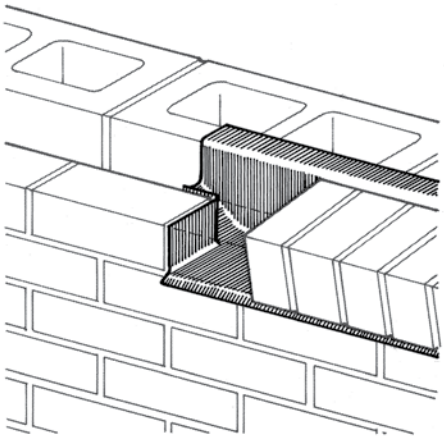
A. Roof Edge (Two Alternatives)



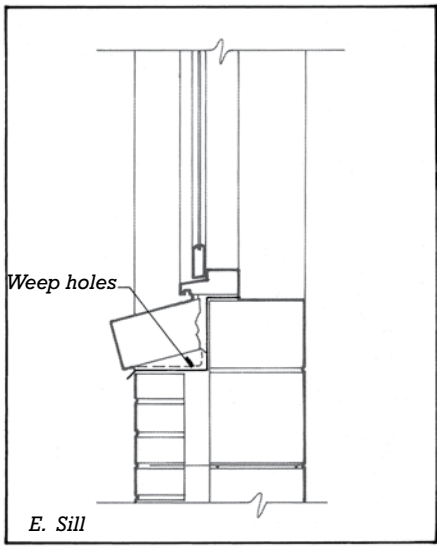
D. Lintel



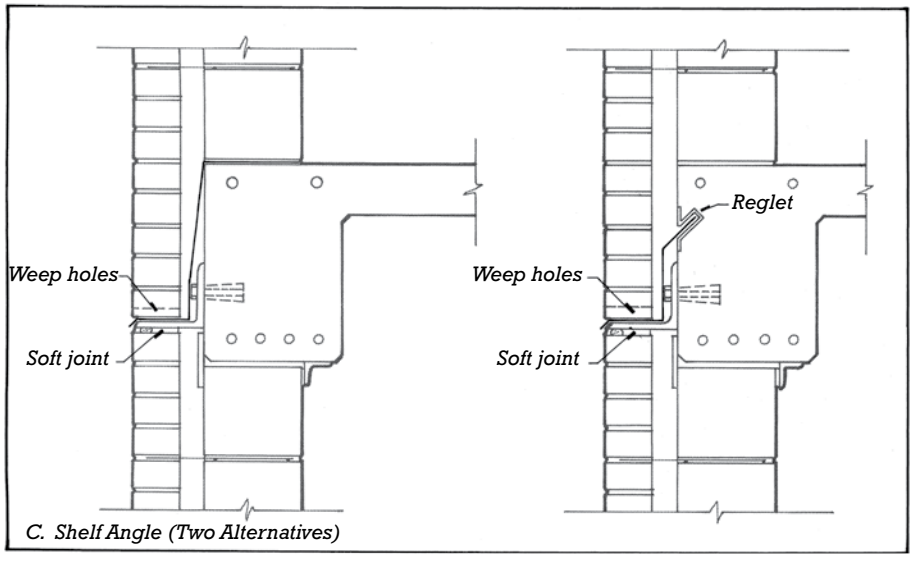
B. Recess or Projection



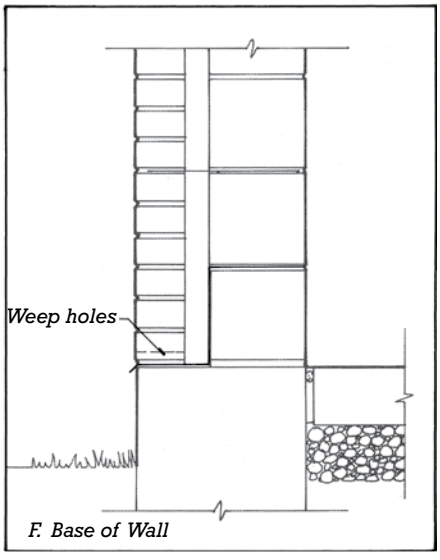
End Dam in Sill Flashing (Lintel Flashing Similar)



E. Sill



C. Shelf Angle (Two Alternatives)



F. Base of Wall

FIGURE 10.5
Mortar deflection material. Strips of tangled matting cut with a keystone pattern are inserted into the bottom of the wall cavity, where they prevent accumulations of mortar from obstructing weep holes. *(Copyright 2007, MortarNet® USA, Ltd. All rights reserved.)*

	Ultimate Compressive Strength	Density
Concrete masonry units	1700–6000 psi *12–41 MPa*	75–145 lb/ft^3 *1200–2320 kg/m^3*
Bricks	2000–20,000 psi *14–140 MPa*	100–140 lb/ft^3 *1600–2240 kg/m^3*
Limestone	1800–33,000 psi *12–230 MPa*	110–170 lb/ft^3 *1760–2720 kg/m^3*
Sandstone	4000–35,000 psi *28–240 MPa*	125–165 lb/ft^3 *2000–2640 kg/m^3*
Marble	7500–27,000 psi *500–190 MPa*	144–170 lb/ft^3 *2310–2720 kg/m^3*
Granite	19,000–45,000 psi *130–310 MPa*	160–170 lb/ft^3 *2560–2720 kg/m^3*

FIGURE 10.6
Ultimate strength and density for bricks, concrete blocks, and building stone.

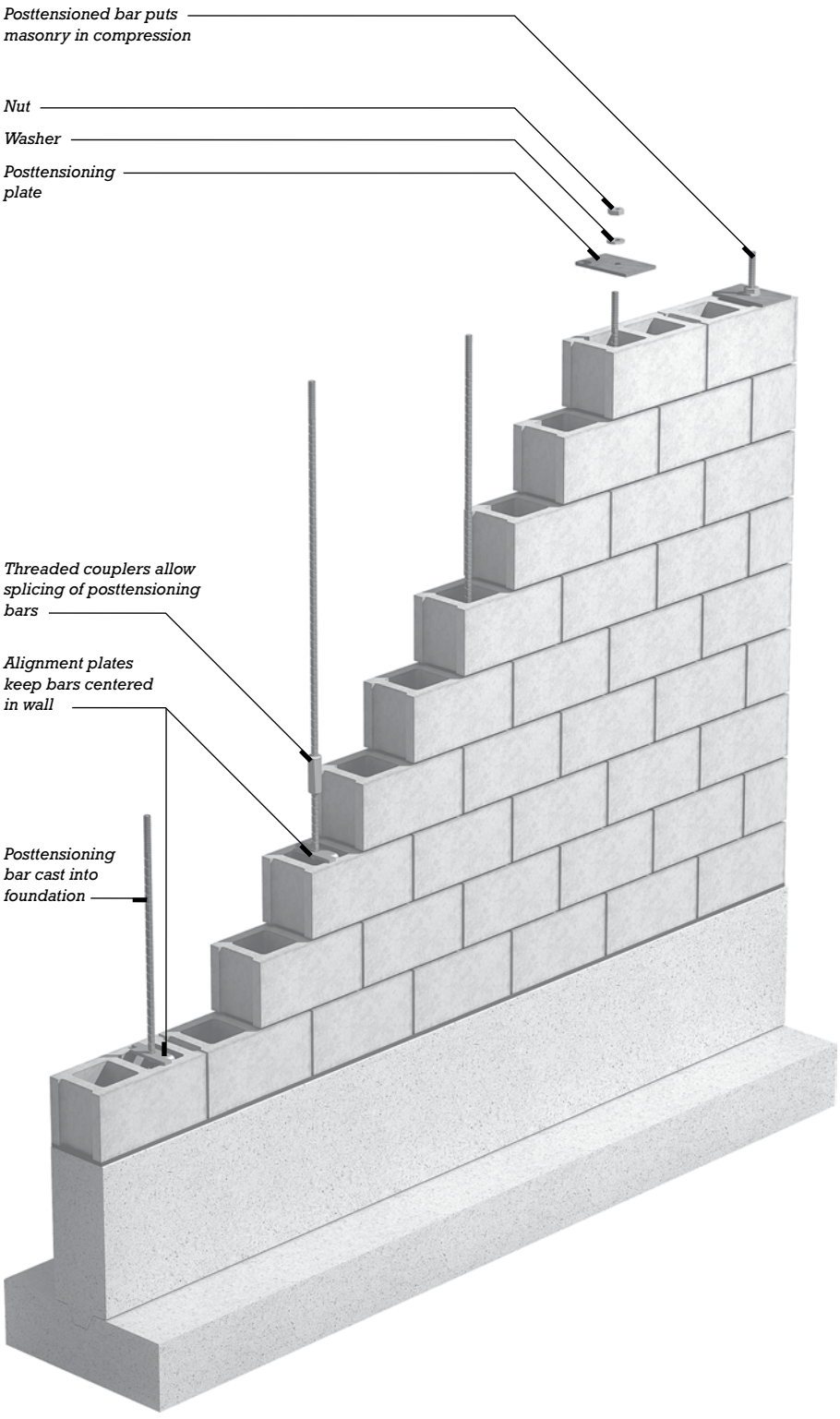


FIGURE 10.7

One system for posttensioning a concrete masonry wall. Short sections of round, threaded high-strength steel bar are joined with threaded couplers as the wall rises. At the base of the wall, the bar is anchored to a threaded insert that has been epoxied into a hole drilled in the concrete foundation. At the top, the bar passes through a steel plate. When the nut at the top end of the bar is tightened, the masonry wall is placed in compression. A load indicator washer tells when the bar is applying sufficient compression to the wall. Load indicator washers are shown in Figure 11.17.

Preliminary Design of Loadbearing Masonry Structures

• To estimate the size of a reinforced brick masonry column, add up the total roof and floor area supported by the column. A 12-inch (300-mm) square column can support up to about 1500 square feet (140 m^2) of area, a 16-inch (400-mm) column 3000 square feet (280 m^2), a 20-inch (500-mm) column 5000 square feet (465 m^2), and a 24-inch (600-mm) column 7000 square feet (650 m^2).

• To estimate the size of a reinforced concrete masonry column, add up the total roof and floor area supported by the column. A 12-inch (300-mm) square column can support up to about 1000 square feet (95 m^2) of area, a 16-inch (400-mm) column 2000 square feet (185 m^2), a 20-inch (500-mm) column 3000 square feet (280 m^2), and a 24-inch (600-mm) column 4000 square feet (370 m^2).

• To estimate the thickness of a reinforced brick masonry loadbearing wall, add up the total width of floor and roof decks that contribute load to a 1-foot (305-mm) length of wall. An 8-inch (200-mm) wall can support up to approximately 600 feet (180 m) of deck and a 12-inch (300-mm) wall about 1000 feet (300 m).

• To estimate the thickness of a reinforced concrete masonry loadbearing wall, add up the total width of floor and roof decks that contribute load to a 1-foot (305-mm) length of wall. An 8-inch (200-mm) wall can support up to approximately 400 feet (120 m) of deck, a 12-inch (300-mm) wall 700 feet (215 m).

These approximations are valid only for purposes of preliminary building layout and must not be used to select final member sizes. They apply to the normal range of building occupancies, such as residential, office, commercial, and institutional buildings and parking garages.

For manufacturing and storage buildings, use somewhat larger members. For more comprehensive information on preliminary selection and layout of a structural system and sizing of structural members, see Edward Allen and Joseph Iano, *The Architect's Studio Companion* (6th ed.), Hoboken, NJ, John Wiley & Sons, 2017.

Spanning Systems for Masonry Bearing Wall Construction

Masonry and Wood Light Frame Construction

So-called *Ordinary construction*, in which the floors and roof are framed with wood light frame joists and rafters and supported at the perimeter on masonry walls, is the fabric of which American city centers largely were built in the 19th and early 20th century. It still finds use today in a small percentage of new buildings and is defined as Type III construction in the International Building Code (IBC). (See Chapter 1 for more information about construction types.) Ordinary construction is essentially balloon framing (Figure 5.2), in which the outer walls of wood are replaced with masonry bearing walls. Balloon framing of the interior loadbearing partitions is used instead of platform framing because it minimizes the sloping of floors that might be caused by wood shrinkage along the interior lines of support. Figure 10.8 shows the essential features of Ordinary construction.

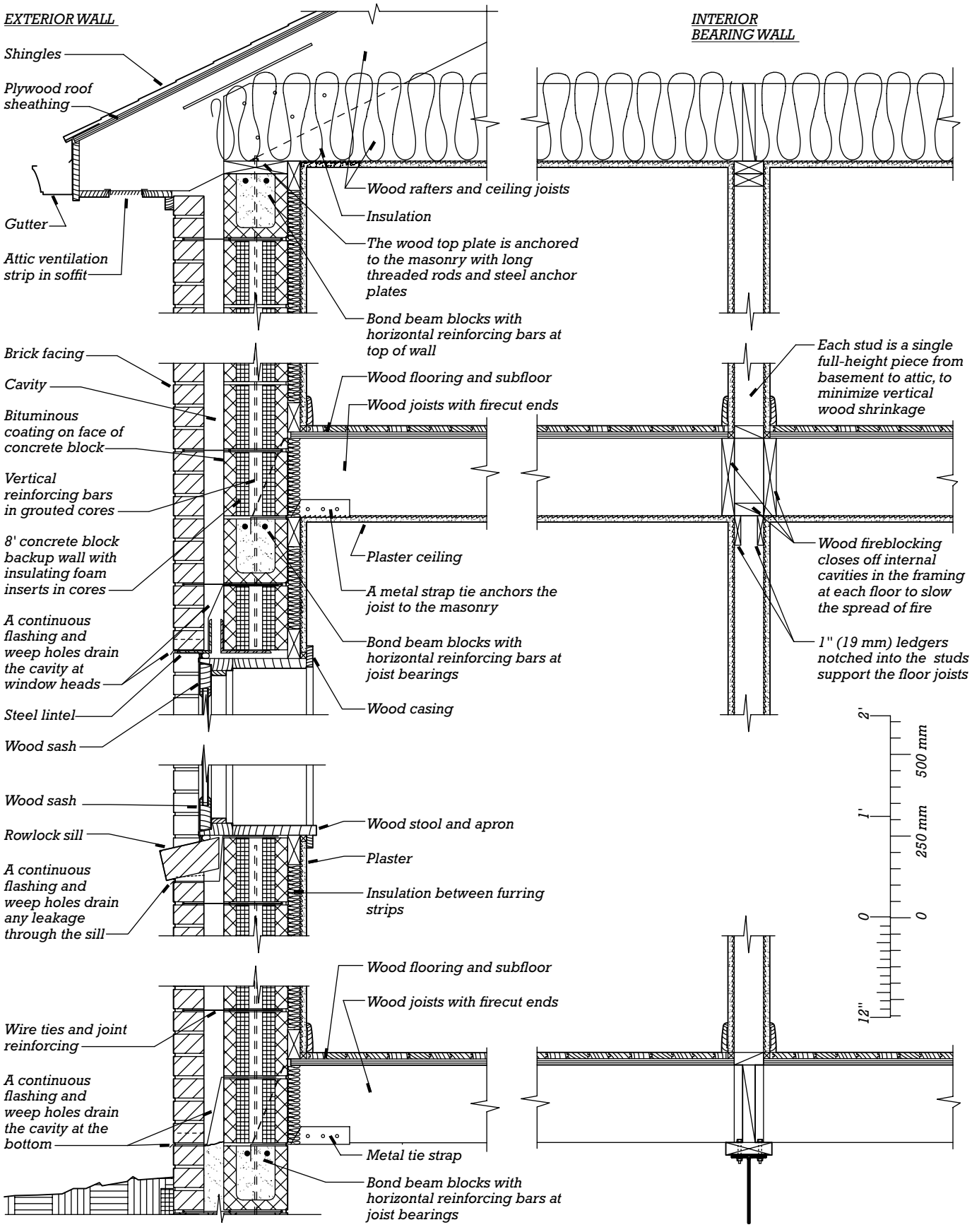
Masonry and Heavy Timber Construction

Masonry exterior walls can also be combined with heavy timber framing and thick timber decking. Because these heavier wood components are slower to catch fire and burn than the nominal 2-inch (38-mm) framing members and thinner structural wood panel decking of Ordinary construction, larger floor areas and greater building heights are permitted. Traditionally referred to as *Mill construction*, today, buildings of exterior masonry and interior heavy timber construction are defined as Type IV-HT construction in the International Building Code and are discussed in more detail in Chapter 4.

Steel and Concrete Decks with Masonry Bearing Walls

Spanning systems of structural steel, sitecast concrete, and precast concrete are frequently used in combination with masonry bearing walls. Figures 10.9 and 10.10 show representative details of two of these combinations. Depending on the degree of fire resistance of the masonry walls and spanning elements, these fully noncombustible systems may be classified under Type I or Type II construction in the IBC.

Figure 10.8
Traditional Ordinary construction, shown here with a cavity wall of brick with a concrete masonry loadbearing wythe. Thermal insulation is installed within the CMU and between wood furring strips on the interior side. The interior is framed with balloon framing of wood studs and joists. At the perimeter of the building, the joists are supported by the masonry wall. The rowlock windowsill detailed here is similar to the one shown in Figure 10.13*c*.


EXTERIOR WALL
INTERIOR BEARING WALL
Shingles
Plywood roof sheathing
Gutter
Attic ventilation strip in soffit
Wood rafters and ceiling joists
Insulation
The wood top plate is anchored to the masonry with long threaded rods and steel anchor plates
Bond beam blocks with horizontal reinforcing bars at top of wall
Brick facing
Cavity
Bituminous coating on face of concrete block
Vertical reinforcing bars in grouted cores
8' concrete block backup wall with insulating foam inserts in cores
A continuous flashing and weep holes drain the cavity at window heads
Steel lintel
Wood sash
Wood flooring and subfloor
Wood joists with firecut ends
Plaster ceiling
A metal strap tie anchors the joist to the masonry
Bond beam blocks with horizontal reinforcing bars at joist bearings
Wood casing
Each stud is a single full-height piece from basement to attic, to minimize vertical wood shrinkage
Wood fireblocking closes off internal cavities in the framing at each floor to slow the spread of fire
1" (19 mm) ledgers notched into the studs support the floor joists
Wood sash
Rowlock sill
A continuous flashing and weep holes drain any leakage through the sill
Wood stool and apron
Plaster
Insulation between furring strips
Wire ties and joint reinforcing
A continuous flashing and weep holes drain the cavity at the bottom
Wood flooring and subfloor
Wood joists with firecut ends
Metal tie strap
Bond beam blocks with horizontal reinforcing bars at joist bearings
2'
1'
0
12"
500 mm
250 mm
0

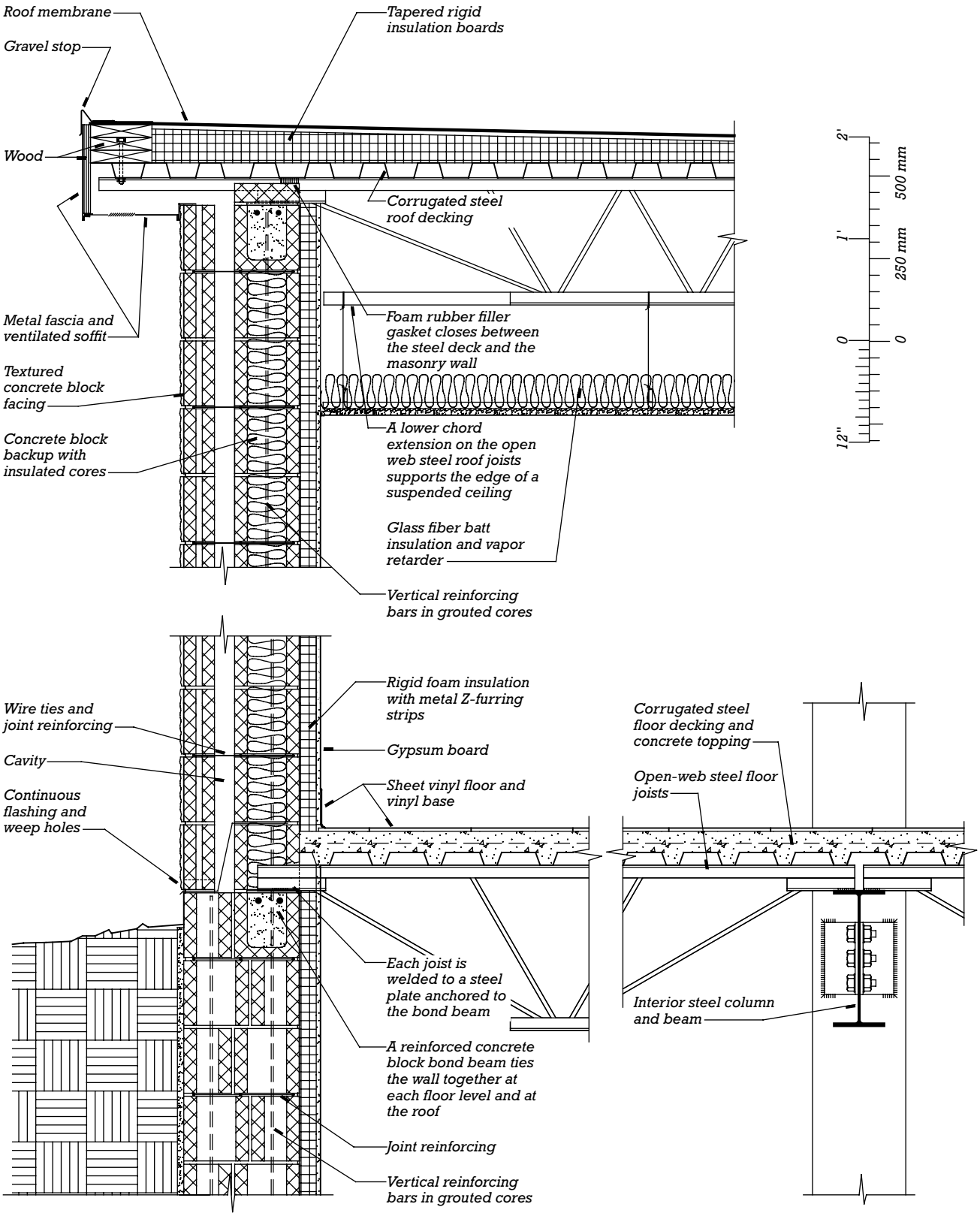


FIGURE 10.9

An example of a concrete masonry exterior bearing wall with a roof and floor of steel open-web joists and corrugated steel decking. Insulation could also be inserted into the wall cavity, as an alternative to the strategies shown here. Because the steel portions of the primary structure are not fire protected, this is classified as Type II-B construction in the IBC.

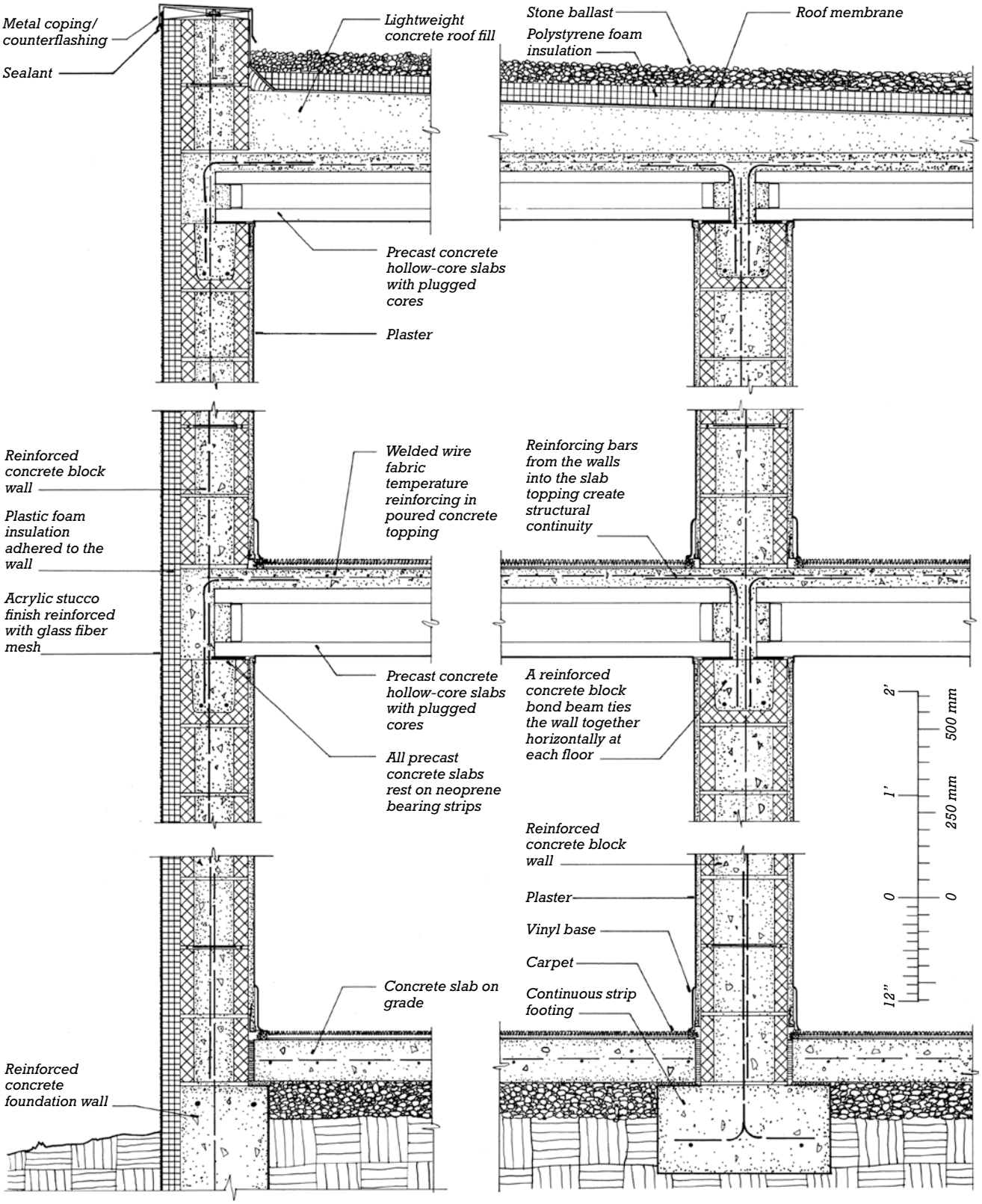


FIGURE 10.10

An example of concrete block exterior and interior bearing walls with precast concrete hollow-core slabs spanning the roof and floors. Full wall reinforcing is shown, with EIFS applied to the outside of the building. (EIFS is discussed further later in this chapter.) Depending on the level of fire resistance achieved by the structural components, this system could be classified as Type I-A, I-B, or II-A construction in the IBC.

Detailing Masonry Walls

Cavity Drainage and Flashings

The traditionally recommended separation between wythes of a cavity wall is not less than 2 inches (50 mm). This provides sufficient space for the masons to keep the cavity free of mortar obstructions while the wall is being built. Where insulation is inserted into the cavity, the remaining clear space within the cavity is maintained at a depth of at least 1 inch (25 mm). Or, if alternative provisions are made to ensure adequate cavity drainage, such as insertion of a continuous drainage mat behind the veneer, the depth of the clear space may be reduced further.

Weep holes at the cavity bottom should be spaced not more than 24 inches (600 mm) horizontally in brick and 32 inches (800 mm) in concrete masonry. Weeps should lie immediately on top of the flashing in the wall to keep the bottom of the cavity as dry as possible. Weeps are formed by leaving open head joints between units, making the weep the full width of the joint and at least 2 inches (50 mm) tall. To prevent insects from taking up residence within the cavity, stainless steel wool or plastic or metal screens may be inserted into the open joints (Figure 10.11). Weeps may also be formed with plastic tubes laid in the head joints as they are mortared (Figure 10.12).

Masonry flashings are used two ways: *External flashings* prevent moisture from penetrating into the wall at vulnerable exposed surfaces. *Internal flashings* (also known as *concealed*

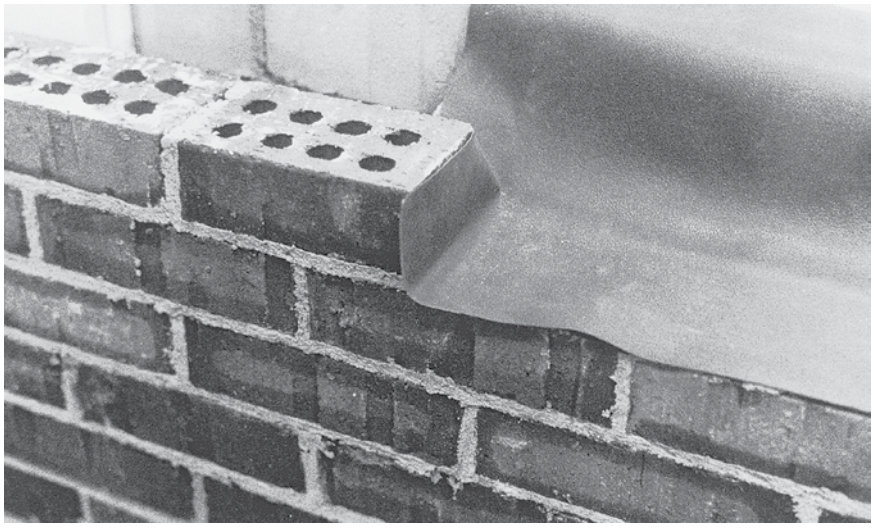
Figure 10.11
An open head joint weep, with a plastic insert to prevent the entry of insects. The thin black line underneath the bottommost mortar joint is the edge of an internal flashing made of modified asphalt. It is being squeezed out of the joint by the weight of the masonry above pressing on this soft material. A better design would add a sheet metal edge that would extend out from the face of the joint and form a more effective drip edge.

Figure 10.12
Internal metal flashings under a rowlock brick windowsill and a soldier course window head. In the window head, weeps formed with plastic tubes are discernible at the bottom of every third brick joint. Weeps in the windowsill flashing are hidden in shadow. Vertical expansion joints, aligned with either side of the window openings, are sealant joints with sand embedded into the surface of the sealant to simulate the appearance of mortar.

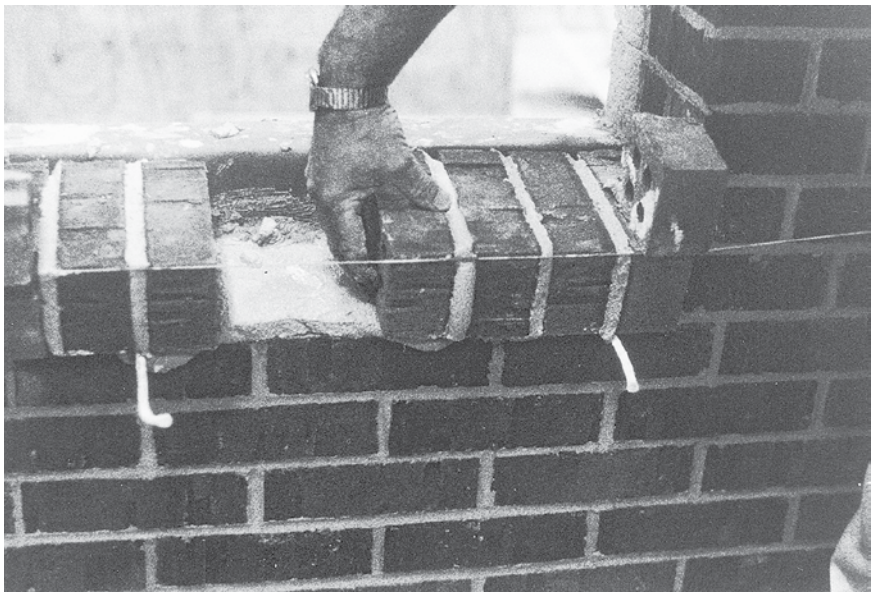
or *through-wall flashings*) catch water that has entered the wall and drain it through weep holes back to the exterior.

The metal *coping* at the top of a masonry parapet (Figure 10.10) is one example of an external flashing, acting to prevent water from entering the wall at this highly exposed location. Flashing at the intersection of a flat roof and a wall parapet is usually constructed in two overlapping parts: a base flashing that is part of the roof membrane and an external metal *counterflashing* (Figure 10.4*A*). The base flashing is formed by turning the roof membrane up, for a height of at least 8 inches (200 mm). The counterflashing is embedded in the masonry wall above and extends downward, lapping over the base flashing. Counterflashings are often made with two interlocking pieces, allowing for easy removal when the roof membrane must be replaced. External flashings may also be used to protect masonry sills and other exposed horizontal or sloping surfaces where water is especially likely to penetrate the masonry.

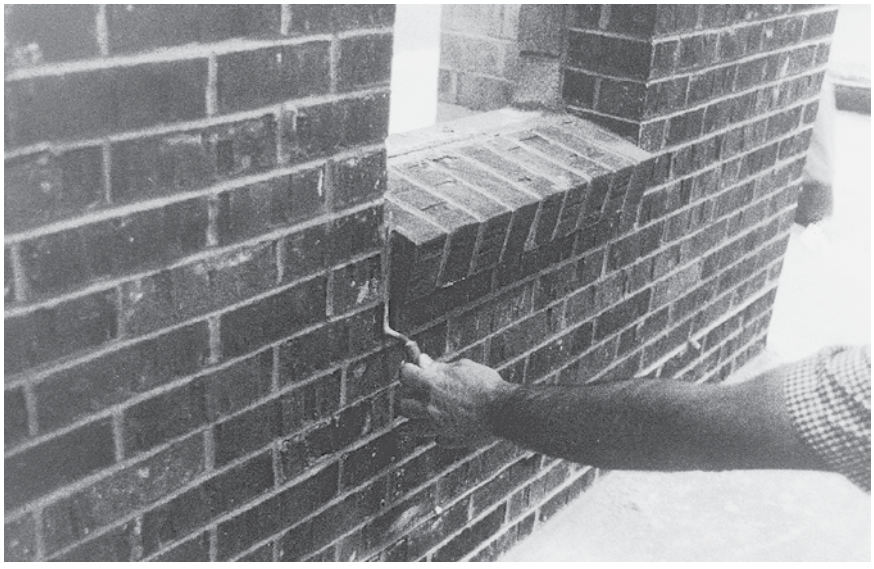
Internal flashings are installed by masons as they construct the wall. We have already discussed the flashing that is placed at the bottom of the wall cavity. Additional flashings are required wherever the cavity is interrupted: for example, at heads of windows and doors, windowsills, shelf angles, and spandrel beams



(*a*)



(*b*)



(*c*)

FIGURE 10.13

Flashing a rowlock brick windowsill with composite flashing sheet. (*a*) The flashing is turned up to form a dam at the end. The projecting portion should be made of sheet metal. (*b*) In this no-longer-used method of forming weep holes, pieces of chord are laid in the bed joint beneath the sloping rowlock sill bricks. These will be pulled out after the mortar has stiffened. (*c*) The finished sill. *(Courtesy of Brick Institute of America.)*

(Figures 10.4*B–F*). At the back of the cavity, the flashing is turned up and overlapped by the water-resistive barrier. In this manner, water draining down the cavity is intercepted and directed toward the exterior. At the outside face of the wall, flashings should extend beyond the wall face and turn down to create a *drip edge* that causes water to fall free of the wall, rather than being drawn under the flashing by capillary action and returning into the wall (Figure 10.12).

Flashings may be made of sheet metal, modified asphalt, synthetic rubber, or composite sheets. *Sheet metal flashings* are the most durable and the most expensive. Copper and stainless steel are best. Galvanized steel eventually rusts and disintegrates; it is acceptable for external flashings where it can easily be replaced when needed, but should not be used for internal flashings. Aluminum is unsuitable for flashings in masonry walls because it reacts chemically with mortar.

Asphaltic membrane flashings are flexible membranes made of polymer-modified asphalts laminated to plastic backings. Most are manufactured with preapplied adhesive on one side, for which reason they are referred to as *self-adhered flashings*. In comparison to metal flashings, they can be more easily shaped and sealed at corners and laps. They are often used in combination with sheet metal flashing, using the metal to span an open cavity or extend beyond the wall to create a drip edge. (The asphaltic membrane is too flexible to support itself across the cavity or form a drip edge, and it cannot be exposed to daylight.)

Composite (*laminated*) *flashings* combine layers of various materials and are intermediate in price. An example is heavy copper foil laminated with glass fiber mesh or other reinforcing material. Flashings of synthetic rubber are the least expensive.

Internal flashings are extremely difficult to replace if they fail in service, and even the most expensive flashing materials cost only a very small fraction of the total price of a masonry wall. So there is little reason to use cheap flashing material in a misguided effort to save money.

Care is required in the installation of flashings. For example, at corners and other junctions where sections of flashing material meet, the pieces should be lapped and soldered or sealed with a suitable mastic. Head and sill flashings should extend beyond the jambs of the opening and terminate in folded *end dams* (Figures 10.4 and 10.13*a*). The end dams ensure that water trapped by the flashing drains back to the exterior of the wall rather than spilling off the end of the flashing within the cavity.

Cavity wall vents, similar to weeps but located close to the top of the wall cavity, may also be part of a cavity wall design. Along with the weeps low in the cavity, these promote air movement through the cavity as an aid to drying. For walls subject to strong, wind-driven rain, vents may be part of pressure-equalized design, as discussed in Chapter 16.

Thermal Insulation

A solid masonry wall is a poor insulator. In a hot, dry climate, the *thermal mass* of a masonry wall—that is, the capacity of an uninsulated masonry wall to store heat and slow its passage—can help to keep the inside of a building cool during the hot day and warm during the cold night. But in most climates, measures must be taken to also improve the thermal resistance of masonry walls.

Masonry walls can be insulated on the outside face, within the wall, and/or on the inside face. Insulation on the outside face is usually accomplished by means of an *exterior insulation and finish system (EIFS)*, which consists of panels of plastic foam that are attached to the masonry and covered with a thin, continuous layer of polymeric stucco reinforced with glass fiber mesh. EIFS is frequently used for insulating existing masonry buildings in cases where the exterior appearance of the masonry need not be retained. An advantage of such a system is that the masonry is protected from temperature extremes and can act to stabilize the interior temperature of the building. Figure 10.10 details a building insulated in this manner, and EIFS is discussed in more detail in Chapter 20.

Insulation within the wall can take several forms. If the cavity is sufficiently wide, the masons can insert slabs of plastic foam insulation against the inside wythe of masonry as the wall is built (Figure 10.3*d–f*). Or, the hollow cores of concrete masonry can be filled with molded-to-fit liners of foam plastic (Figure 10.14). Insulating the cores of concrete blocks does not slow the passage of heat through the webs of the blocks or through portions of the masonry that have been reinforced and fully grouted, so is of limited effectiveness, especially in heavily reinforced walls.

The inside surface of a masonry wall can be insulated by attaching insulation to the face of the wall along with wood or metal *furring strips* (Figures 10.8, 10.9, and 10.15). The gypsum wallboard or other interior finish material is then fastened to the furring strips. Furring the wall finish off the face of the masonry can also solve another chronic problem of masonry construction by creating a space in which electrical wiring and plumbing can easily be concealed.

FIGURE 10.14
A concrete masonry unit and insulation system. The webs of the blocks are minimal in area, to reduce thermal bridging where they pass through the foam. The specially shaped polystyrene inserts provide insulation even in parts of the wall with grouted reinforcing. Grouting has not yet occurred in this photograph. *(Courtesy of Korfil, Inc., P.O. Box 1000, West Brookfield, MA 01585.)*

FIGURE 10.15
A worker installs foam plastic insulation on the interior of a concrete masonry wall, using a system of steel furring strips in which only isolated clips, visible in this photograph, contact the masonry wall to minimize thermal conduction through the metal. The furring strips serve as a base to which interior finish panels such as gypsum board can be attached. *(Courtesy of W. R. Grace & Co.)*

Special Problems of Masonry Construction

Expansion and Contraction

Masonry walls expand and contract slightly in response to changes in both temperature and moisture content. Thermal movement is relatively easy to quantify (Figure 10.16). Moisture movement is more difficult: New clay masonry units tend to absorb water and expand gradually under normal atmospheric conditions. New concrete masonry units usually shrink somewhat as they give off excess water following manufacture. Expansion and shrinkage in masonry materials are small compared to the moisture movement in wood or the thermal movement in plastics or aluminum. Still, these changes must be taken into account in the design of the building by providing joints of the appropriate types to prevent excessive forces that could crack or spall the masonry. (See the accompanying sidebar, "Movement Joints in Buildings.")

Three different kinds of movement joints are used in masonry. Expansion joints are breaks in the material that can close or open to accommodate expansion and contraction due to changes in moisture content, temperature, structural movements, or other effects. Control joints are intentionally created planes of weakness that can open to accommodate shrinkage in masonry surfaces, usually during initial curing. Isolation joints are placed at junctions between masonry and other materials, or between new masonry and old masonry, to accommodate differences in movement between these materials. Figures 10.17 and 10.18 illustrate the placement of movement joints in masonry walls. An example of expansion joints aligned with window openings can be seen in Figure 10.12. Movement joints are also critical in masonry facings applied over multistory structural frames of steel or concrete, to prevent damage to the masonry when the frame deflects under load, as discussed in Chapter 20.

Joint reinforcing must be interrupted at movement joints so that it does not restrain the opening or closing of the joint. To prevent out-of-plane displacements of the wall, various kinds of vertically interlocking details may be used, as seen in Figure 10.19. Most movement joints in masonry walls are closed with flexible sealants to prevent air and water from passing through.

Masonry is a massive material, taking forms permitted by the law of gravity. Our vocabulary of masonry forms was developed in buildings which became essays about gravity—great weights piled high, buttresses braced against the thrust of arched vaulting. Long after the internal steel frame relieved the need for such forms, they still retain meaning for us through their historical references and in their familiarity. The basic masonry forms have become symbols.

—Michael Shellenbarger, *Landmarks: A Tradition of Portland Masonry Architecture*, 1984

Material	Coefficient of Linear Thermal Expansion In./in-°F	mm/mm-°C
Clay or shale brick masonry	3.6×10^{-6}	6.5×10^{-6}
Lightweight concrete masonry	4.3×10^{-6}	7.7×10^{-6}
Limestone	4.4×10^{-6}	7.9×10^{-6}
Granite	4.7×10^{-6}	8.5×10^{-6}
Normal weight concrete masonry	5.2×10^{-6}	9.4×10^{-6}
Marble	7.3×10^{-6}	13.1×10^{-6}
Normal weight concrete	5.5×10^{-6}	9.9×10^{-6}
Clay or shale brick masonry	3.6×10^{-6}	6.5×10^{-6}
Structural steel	6.5×10^{-6}	11.7×10^{-6}

Figure 10.16
Average linear coefficients of thermal expansion for some masonry materials. (See the Appendix for additional such data.)

Figure 10.18
Expansion joints in masonry walls should also be located at discontinuities in the wall, where cracks due to expansion and contraction are most likely to occur.

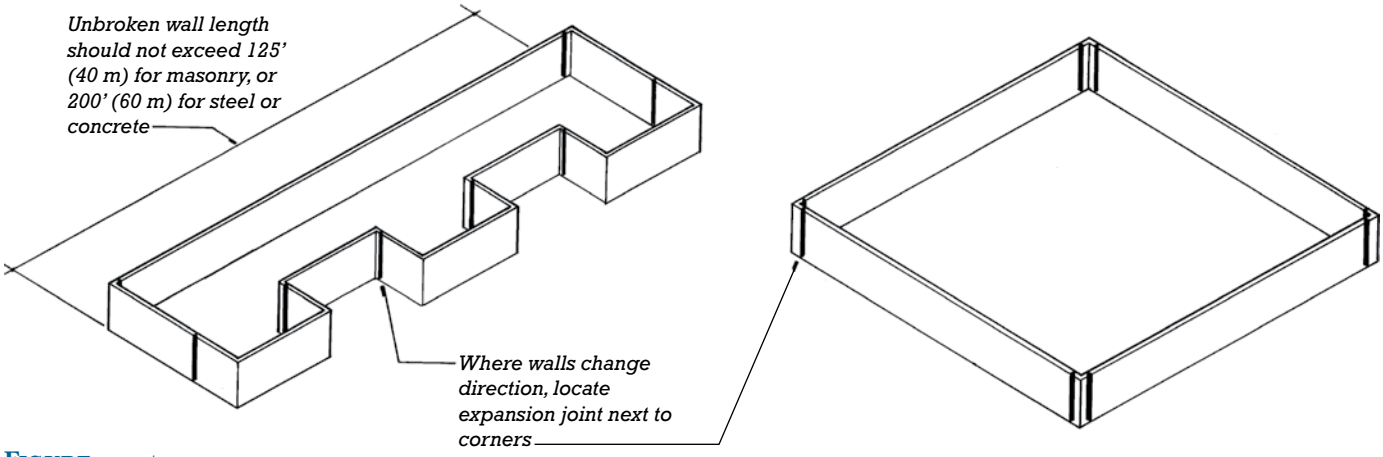
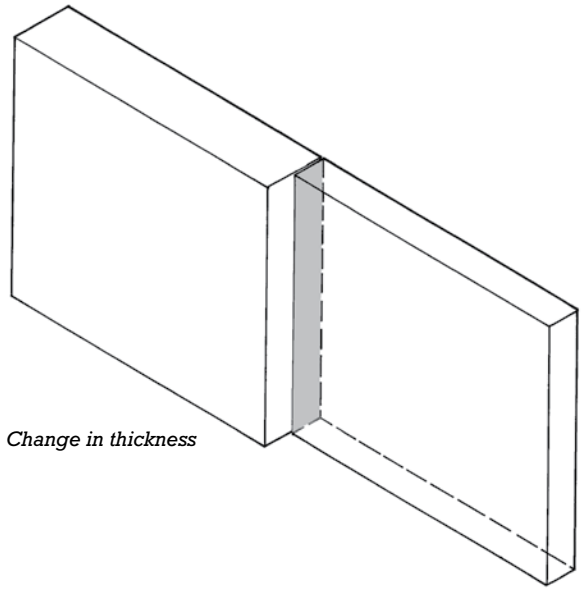
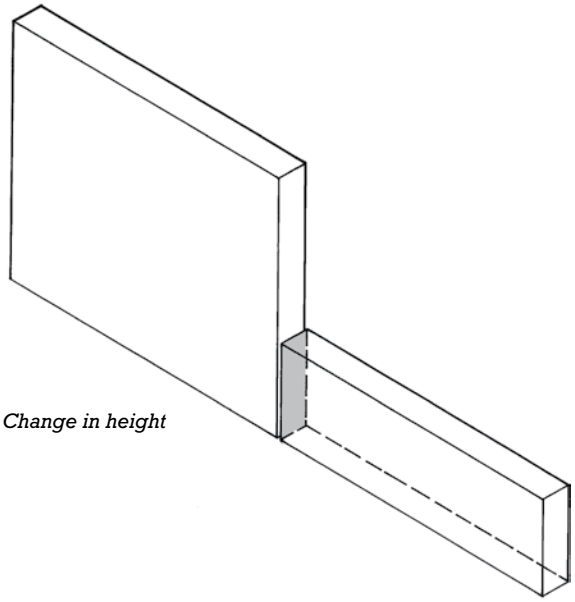
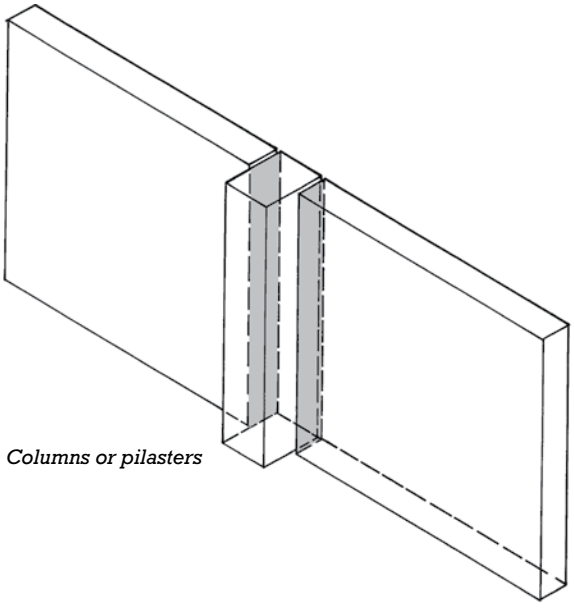
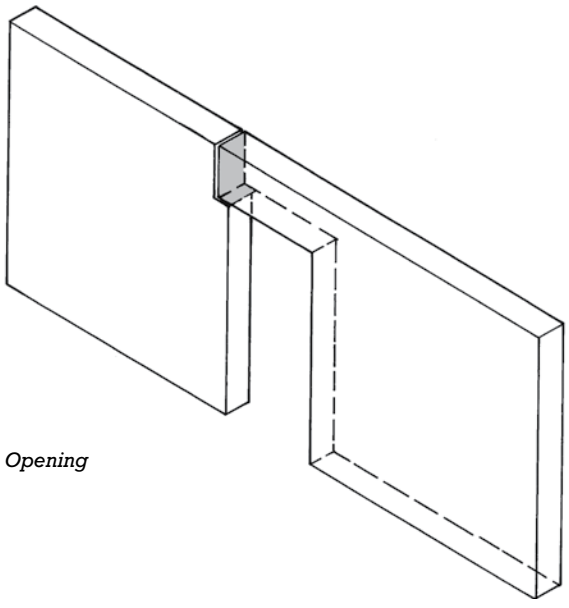


FIGURE 10.17
Expansion joints in masonry walls should be located near changes of direction in the walls.









Movement Joints in Buildings

Buildings and their materials are constantly in motion. Many of these motions are cyclical and never-ending. Some are caused by temperature changes: All materials shrink as they grow cooler and expand as they become warmer, each doing so at its own characteristic rate (see Figure 10.19 and the table of coefficients of thermal expansion in the Appendix). Some are caused by changes in moisture content: Most porous materials grow larger when wetted by water or humid air and smaller when they dry out, also at rates that vary from one material to another. These cyclical motions caused by temperature and moisture can occur on a seasonal basis (warm and moist in summer, cold and dry in winter), and they can also occur in much shorter cycles (warm days, cool nights; warm when the sun is shining on a surface, cool when a cloud covers the sun). Some motions are caused by structural deflections, such as slight sagging of beams, girders, joists, and slabs under imposed loads. These motions can be long term for dead loads and for floors supporting stored materials in a warehouse. Deflections can be medium term for snow on a roof and very short term for walls resisting gusting winds. Some motions are one-time phenomena: Concrete and stucco shrink as they cure and dry out, whereas gypsum plaster expands upon curing. Clay bricks expand slightly over time as they absorb atmospheric moisture. Concrete columns shorten slightly, and concrete beams and slabs sag a bit due to plastic creep of the material during the early years of a building's life; then they stabilize. Posttensioned slabs and beams grow measurably shorter as they take up the compression induced by the stretched steel tendons. Soil compresses under the pressure of the foundations of a new building and then, in most cases, stops moving.

Chemical processes can cause movement in building components: If a steel reinforcing bar rusts, it expands, cracking the concrete around it. Solvent-release sealants shrink as they cure. Some plastics shrink and crack upon prolonged exposure to sunlight. Motion can also be caused by the freezing expansion of water, as happens in the upward heaving of insufficiently deep footings during a cold winter, or in the spalling of concrete and masonry surfaces exposed to wetting and freezing.

Most of these motions are small in magnitude, but they occur in buildings of every size and every material. If they are ignored in design and construction, they can cause aesthetically unattractive damage to finishes or more serious distortions and failures of building components.

We accommodate these inevitable movements in buildings in two ways: In some cases, we strengthen a material to enable it to resist the stress that will be caused by an anticipated movement, as we do in adding shrinkage–temperature steel to a concrete slab. In most cases, however, we install movement joints in the fabric of the building that are designed to allow the movements to occur without damage. We locate these joints in places where we anticipate maximum potential distress from expected movements. And we place them at regular intervals in large surfaces and assemblies to relieve cumulative stresses. A building that is not provided with suitable movement joints will make its own joints by cracking and spalling at points of maximum stress, creating a situation that is unsightly at best and sometimes dangerous or catastrophic.

Types of Building Joints

Figure A defines two broad classifications of building joints, movement

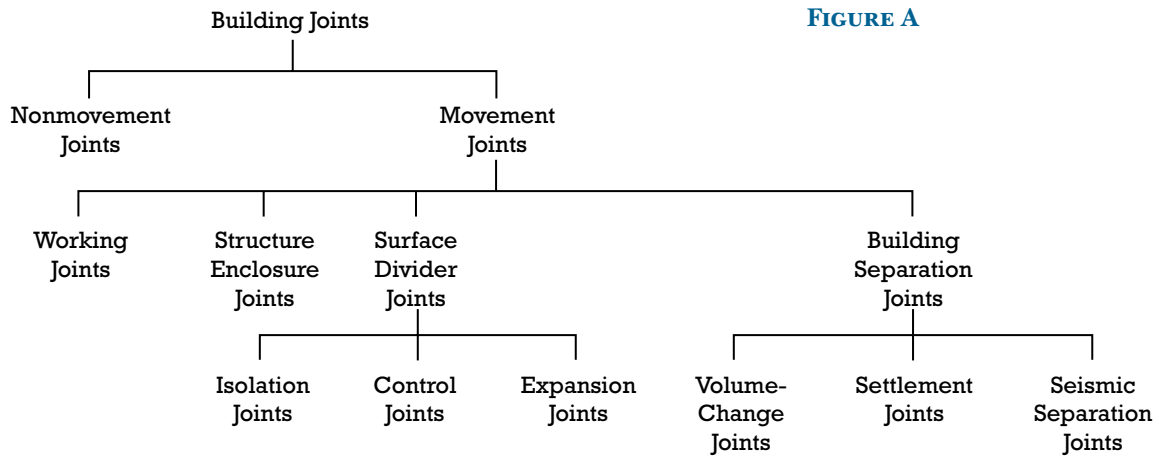


FIGURE A

and nonmovement. *Nonmovement joints* include most types of joints that are used to connect pieces of material in a building: joints such as the nailed connections in the wooden frame of a house, mortar joints between masonry units, welded and bolted connections in a steel frame, and joints between pours of concrete. A nonmovement joint can be made to move only by overloading the joint, as in the pulling-apart of a nailed connection, the slipping of steel members in a bolted connection, or the cracking of a weld, mortar joint, or concrete slab.

Movement joints are of many different kinds. What they have in common is a designed-in ability to adjust to expected amounts of motion without distress.

- The simplest movement joints are *working joints*, which are designed into various building materials and created in the normal process of assembling a building. An excellent example is the ordinary shingled roof, which is made up of small units of material that are applied in an overlapping pattern so that small amounts of thermal or moisture movement in the underlying roof structure or in the shingles themselves can be tolerated without distress (Figure 17.35). Other examples are wood bevel siding (Figure 6.18), which is nailed in such a way that moisture expansion and contraction are provided for; the metal clips and pans from which a sheet metal roof is assembled (Figure 17.43), which slip as necessary to allow for thermal movement; and most types of sealant joints and glazing joints (Chapters 16 and 18).
- *Structure/enclosure joints* separate structural from nonstructural elements so that they will act independently. A simple example is the deflection track sometimes provided at the top of a metal-framed interior partition to allow the structure above to deflect without imparting loads into the nonbearing wall framing (Figure 23.2*b*). Another important example of a structure/enclosure joint is the soft joint that is placed just beneath a shelf angle that supports a masonry veneer (Figures 10.4*C* and 20.3); like the joint at the top of a partition, it prevents a nonstructural element (in this case, a brick facing) from being subjected to a structural load for which it is not designed. Many other cladding attachment details shown in Chapters 20 and 21 are designed to allow the structural frame of the building and the exterior skin to move independently of one another, and these attachments are always associated with soft sealant or open joints in the skin panels.
- *Isolation joints* separate materials or assemblies that must be able to move independently without interfering with one another. For example, when an existing building is altered or enlarged, isolation joints may be inserted between old and new construction to allow normal, one-time movements to take place in the new materials without disturbing the original construction. Or, where a concrete slab on grade abuts columns or walls, isolation joints are provided to prevent unintentional restraint of the slab that could lead to cracking. The last drawing in Figure 10.19, Figure 14.3*c*, and the joint filler strip between the concrete slab and concrete wall shown in Figure 5.6 are all examples of such joints. (Structure/enclosure joints can also be considered one particular type of isolation joint.)
- *Control joints* are deliberately created lines of weakness along which cracking will occur as a surface of brittle material shrinks, relieving the stresses that would otherwise cause uncontrolled or random cracking. The regularly spaced grooves across concrete sidewalks are control joints; they channel the cracking tendency of the pavement into an orderly pattern of straight lines rather than jagged, irregular cracks. Control joints for plaster are shown in Figure 23.11.
- *Expansion joints* are open seams that can close and open to allow expansion and contraction to occur in adjacent areas of material. Expansion joints in brick walls permit the bricks to expand slightly under moist conditions (Figure 10.19). Expansion joints in aluminum curtain wall mullions (Figure 21.13) allow the elements of the wall to increase in size when warmed by sunlight and to shorten when they cool.
- Control joints and expansion joints should be located at geometric discontinuities such as corners, changes in the height or width of a surface, and openings. In long or large surfaces, they should also be spaced at intervals that will relieve the expected stresses in the material before those stresses rise to levels that can cause damage.
- *Building separation joints* divide a large or geometrically complex building mass into smaller, discrete structures that can move independently of one another. Building separation joints can be classified into three types: volume-change joints, settlement joints, and seismic separation joints.
- Large-scale effects of expansion and contraction caused by temperature and moisture are relieved by *volume-change joints*. These are generally placed at horizontal or vertical discontinuities in the massing of

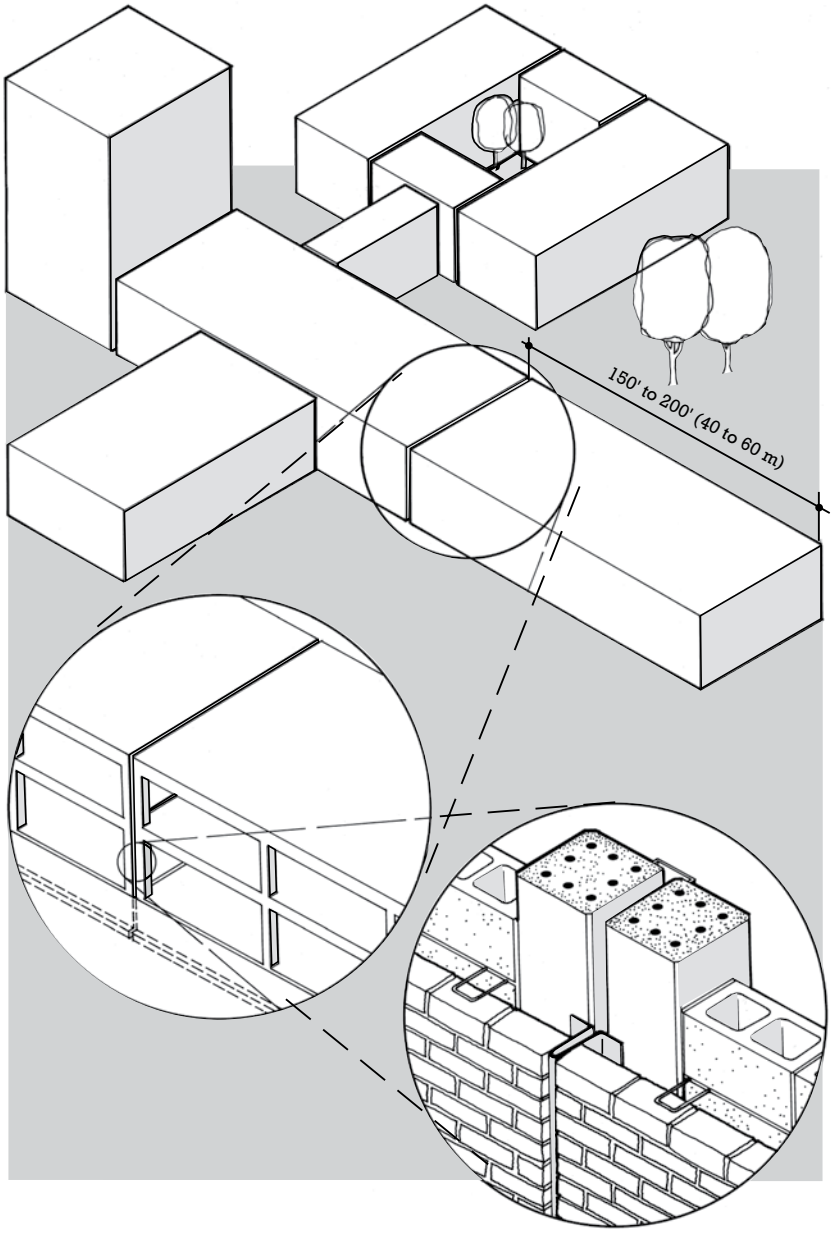
Movement Joints in Buildings *(continued)*

the building, where cracking would be most likely to occur (Figure B). They are also located at intervals of 150 to 200 feet (40 to 60 m) in very long buildings, the exact dimension depending on the nature of the materials and the rate at which dimensional changes occur.

- *Settlement joints* are designed to avoid distress caused by different rates of anticipated foundation settlement between different portions of a building, as between a high-rise tower and a connected low-rise wing, or between portions of a building that bear on different soils or have different types of foundations.
- *Seismic separation joints* are used to divide a geometrically complex building into smaller units that can move independently of one another during an earthquake. (Buildings in seismic zones should also be detailed with structure/enclosure joints that permit the frame of the building to deform during an earthquake without damaging brittle cladding or partition elements.)

Building separation joints are created by constructing independent structures on either side of the plane of the joint, sometimes with entirely separate foundations, columns, and slabs (Figure B). Each of these independent structures is small enough and compact enough in its geometry that it is reasonable to believe that it will move as a unit in response to the forces that are expected to act upon it.

Figure B Interactive Exercise



Detailing Movement Joints

The first imperative in detailing a movement joint is to determine what types of movement the joint must accommodate. This is not always simple. Often the same joint is called upon to perform simultaneously in several of the ways that are outlined here—as a volume-change joint, a settlement joint, and a seismic joint, for example. A joint in a composite masonry wall may serve as both an expansion joint for the brick facing and a control joint for the concrete masonry backup. Once the functions of a joint have been determined, the expected character and magnitude of motion can be estimated with the aid of standard technical reference works, and the joint can then be designed accordingly.

It is important that any structural materials that would restrict movement be discontinued at a movement joint. Reinforcing bars or welded wire fabric are often cut (in whole or in part) at control joints in masonry and concrete. Expanded metal lath is interrupted at control joints in plaster or stucco. The primary loadbearing frame of a building is interrupted at building separation joints. At the same time, it is often important to detail a movement joint so that it will maintain a critical alignment of one sort or another. Figure 10.19 shows several expansion and control joints that use interlocking masonry units or hard rubber gaskets to avoid out-of-plane movement across the joint. In concrete slabs, smooth, greased, closely spaced steel dowels may be inserted across an expansion joint; these permit the joint to move while ensuring that the slab will remain at the same level on both sides of the joint. The curtain wall mullion in Figure 21.13 allows for movement along one axis while maintaining alignment along the two other axes.

Joints must often be designed to stop the passage of heat, air, water, light, sound, and fire. Some must carry traffic, as in the case of joints in floors or bridge pavements. All must be durable and maintainable, while simultaneously adjusting to movement and maintaining an acceptable appearance. Each joint must be detailed to allow the expected direction and extent of movement: Some joints will have to operate only in a push-pull manner, while others are expected to accommodate a shearing motion, or even a twisting motion as well. The exterior joint closure is usually obtained by means of a bellows of metal or synthetic rubber (inset detail, Figure B). Some typical interior joint closures are shown in Figure 22.7.

Every designer of buildings must develop a sure sense of where movement joints are needed in buildings and the knowledge of how to design them. This is neither quick nor easy to do, for the topic is large and complex, and authoritative reference material is widely scattered. Numerous buildings are built each year by designers who have not acquired this intuition. Many of these buildings are filled with cracks even before they have been completed. This brief essay and the related illustrations throughout the book are intended to create an awareness of the problem of movement in buildings and to establish a framework that the reader can fill in with more detailed information over time.

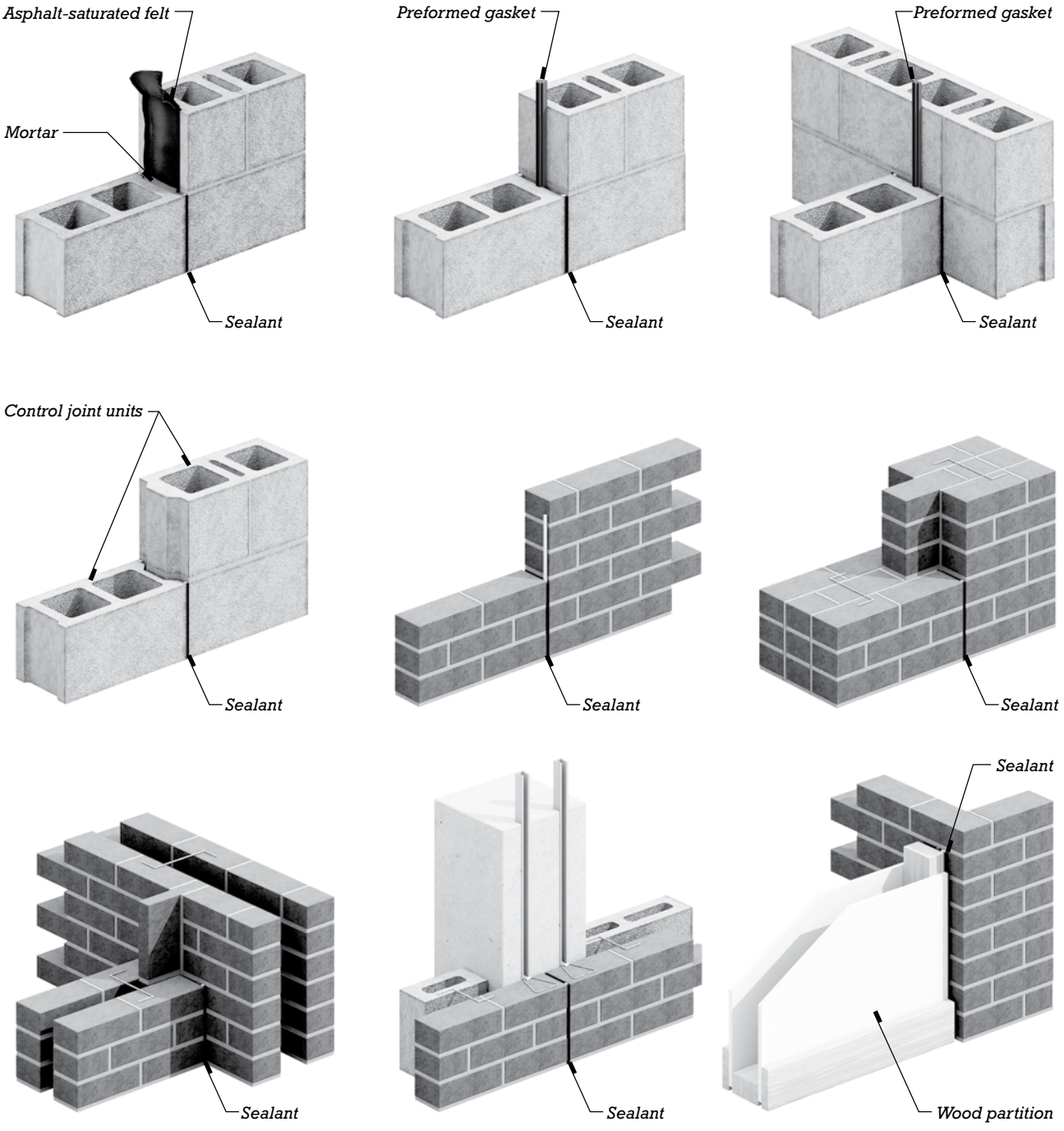


FIGURE 10.19
Some ways of allowing for movement in masonry construction. Notice that in many of these details the masonry units interlock to prevent out-of-plane movement of the walls. Detailing of sealant joints is discussed in Chapter 16.

Efflorescence

Efflorescence is a fluffy crystalline powder, usually white, that sometimes appears on the surface of a wall of brick, stone, or concrete masonry. It consists of one or more water-soluble salts that were originally present either in the masonry units or in the mortar. These were brought to the surface and deposited there by water that seeped into the masonry, dissolved the salts, and then migrated to the surface and evaporated. Efflorescence can usually be avoided by choosing masonry units that have been shown by laboratory testing not to contain water-soluble salts, by using clean ingredients in the mortar, and by minimizing water intrusion into the masonry construction. Most types of efflorescence form soon after the completion of construction and are removed with water and a brush. Although efflorescence is likely to reappear after such a washing, it will normally diminish and finally disappear with time as the salt is gradually leached out of the wall. Efflorescence that forms for the first time after a period of years is an indication that water has only recently begun to enter the wall, and is best controlled by investigating and correcting the source of leakage.

Mortar Joint Deterioration

Mortar joints are the weakest link in most masonry walls. Water running down a wall tends to accumulate in the joints, where cycles of freezing and thawing weather can gradually *spall* (split off flakes of) the mortar in an accelerating process of destruction that eventually creates water leaks and loosens the masonry units. To forestall this process as long as possible, a suitably weather-resistant mortar formulation must be used, and joints must be well filled and tightly compacted at the time the masonry is laid. Even with these precautions, a masonry wall in a severe climate will show substantial joint deterioration after many years of weathering and may require *repointing*: a process of raking and cutting out the defective mortar and replacing it with fresh mortar. Repointing may also sometimes be referred to as *tuckpointing*, although this term more properly refers to a special treatment of mortar joints with contrasting mortar colors.

Moisture Resistance of Masonry

Most masonry materials, including mortar, are porous and can conduct water from one side of the wall to the other. Water can also enter a wall through small cracks that may develop between masonry units and the mortar that surrounds them. Managing water penetration of masonry begins by specifying appropriate types of masonry units, mortar, and joint tooling. Cavity wall construction may be considered rather than solid wall construction. Properly designed external and internal flashings should be provided. The construction process should be supervised to ensure that mortar joints are free of voids, flashings and weeps are properly installed, and cavities are kept clean. Masonry walls should be protected against excessive wetting to the extent practical through proper roof drainage and sheltering roof overhangs. Beyond these measures, consideration may also be given to coating the wall with stucco, paint, or *clear water repellent*. It is important that any exterior coating be permeable to water vapor to avoid blistering and rupture of the coating from outward vapor migration. Masonry primer/sealers and paints based on portland cement fill the pores of the wall without obstructing the outward passage of water vapor. Other latex-based or elastomeric coatings that are suitably breathable and intended for application over masonry may also be used. When exterior walls are constructed of solid masonry, *integral water repellents* may be added to the mortar, and if concrete masonry units are used, to the concrete from which these are made as well.

Below grade, masonry should first be parged (plastered on the outside) with two coats of Type M mortar to a total thickness of ½ inch (13 mm) to seal cracks and pores. After the parging has cured and dried, it can be coated with dampproofing or waterproofing, as discussed in Chapter 2.

Cold- and Hot-Weather Construction

Mortar cannot be allowed to freeze before it has cured; otherwise, its strength and watertightness may be seriously impaired. In cold climates, special precautions include keeping masonry units and sand dry, protecting them from freezing temperatures prior to use, warming the mixing water (and sometimes the sand as well) to produce mortar at an optimum temperature for workability and curing, using a Type III (high early strength) cement to accelerate the curing of the mortar, and mixing the mortar in smaller quantities so that it does not cool excessively before it is used. The masons' workstations should be protected from wind with temporary enclosures. They should also be heated if temperatures inside the enclosures do not remain above freezing. The finished masonry must be protected against freezing for at least two to three days after it is laid, and the tops of walls should be protected from rain and snow.

In hot weather, mortar may dry excessively before it cures. Some types of masonry units may have to be dampened before laying so that they do not absorb too much water from the mortar. It is also helpful to keep the masonry units and mortar ingredients, as well as the masons' workstations, in the shade.

Masonry Paving

Brick, concrete, and stone masonry can all be used as paving materials for both pedestrian and vehicular surfaces. Units may be laid dry over a thin layer of sand and a gravel base, or they may be set in mortar or asphalt over a concrete slab (Figure 10.20).

Permeable (or *porous*) *unit paving* systems allow rainwater to pass through the paving system and infiltrate into the soil beneath, rather than flow over the surface of the paving and into a municipal stormwater collection system. Pavements can be made permeable by spacing conventional paving units to leave sand or planted soil in between, or by manufacturing pavers with sufficient openings or permeability for water to freely flow through the pavers themselves.

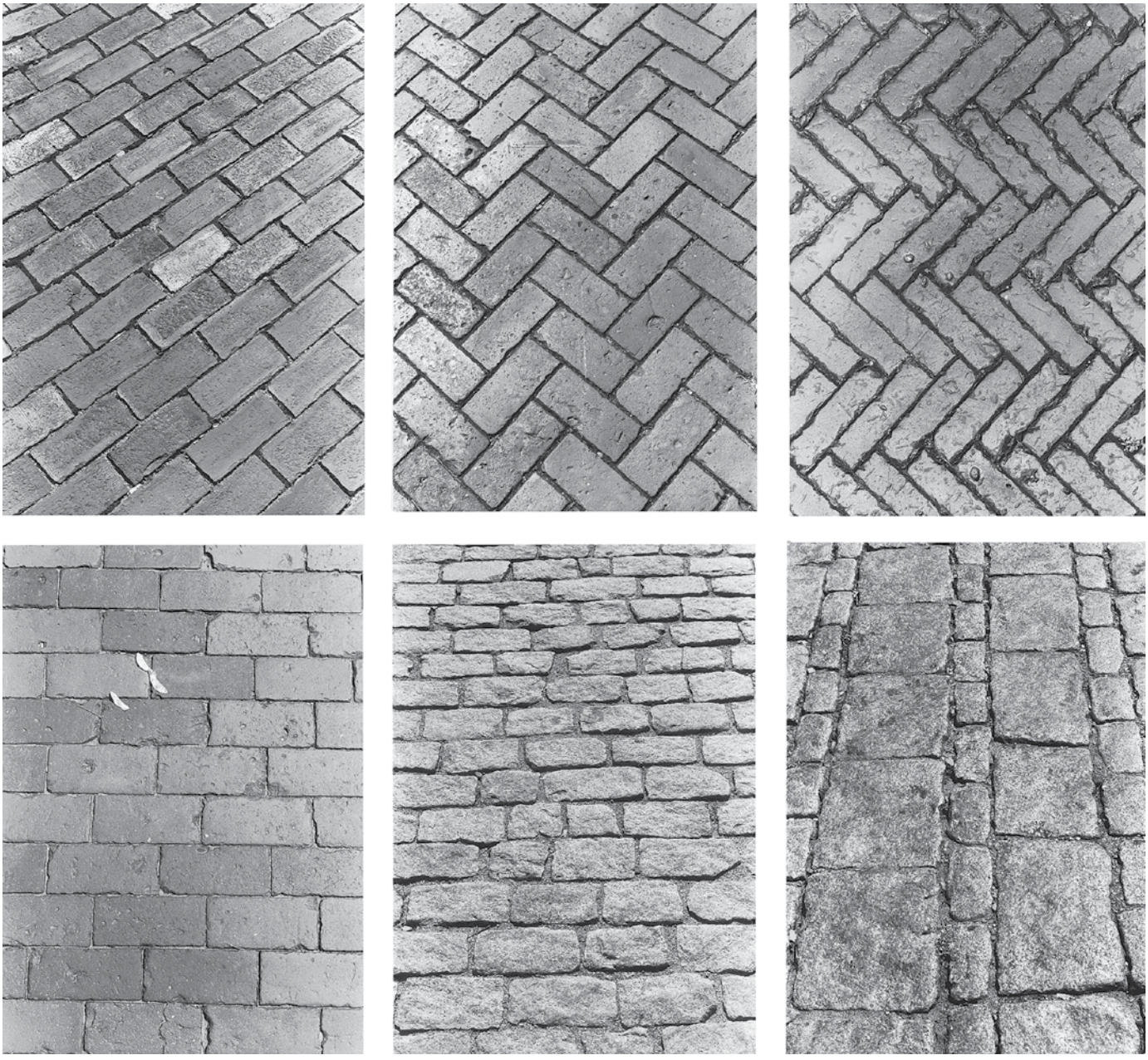


Figure 10.20
Some masonry paving patterns in brick and granite. All six of these examples are laid without mortar in a bed of sand. *(Photos by Edward Allen.)*

Interactive Exercise

Masonry and the Building Codes

Because masonry construction is noncombustible, it can be used in any building code construction type, as long as it meets necessary fire resistance rating requirements (Figure 1.5). Typical ratings for various brick and concrete masonry wall types are given in Figure 10.21. Walls made of masonry are naturally effective and durable barriers to the passage of fire, making them well suited for use as fire walls and other types of fire-resistant separations within and between buildings.

Due to their mass, masonry walls are also effective in limiting the transmission of sound from one space to another. Sound Transmission Class (STC) ratings for brick and concrete masonry walls, also listed in Figure 10.21, allow comparison of the acoustical properties of these walls with those of other partition systems discussed in Chapter 23.

Uniqueness of Masonry

Masonry is often chosen as a construction material for its association in people's minds with beautiful buildings and architectural styles of the past, and with the qualities of permanence and solidity (Figures 10.22 and 10.23). It is often selected for its unique colors, textures, and patterns; for its fire resistance; and for its easy compliance with building code requirements for noncombustibility and fire resistance. Masonry is often chosen, too, because it is economical. Although masonry construction is labor intensive, it can create a high-performance, long-lasting structure and enclosure in a single operation by a single trade, bypassing the difficulties that are frequently encountered in managing the numerous trades and subcontractors needed to erect a comparable building of other materials.

Masonry construction, like wood light frame construction, is carried out with small, relatively inexpensive tools and machines on the construction site. Unlike steel and concrete construction, it does not require (except in the case of ashlar stonework) a large and expensively equipped shop to fabricate the major materials prior to erection. It shares with sitecast concrete construction the long construction schedule that requires special precautions, and can encounter delays during periods of very hot, very cold, or very wet weather. In general, however, it does not require an extensive period of preparation and fabrication in advance of the beginning of construction, because it uses standardized units and materials that are put into final form as they are placed in the building.

From the beginning of human civilization, masonry has been the medium from which we have created our most nearly permanent, most carefully crafted, most highly prized buildings. It has given us the massiveness of the Egyptian pyramids, the inspirational elegance of the Parthenon, and the light-filled loftiness of the great European cathedrals, as well as the reassuring coziness of the fireplace, the brick cottage, and the walled garden. Masonry can express our highest aspirations and our deepest yearnings for rootedness in the earth. It reflects both the tiny scale of the human hand and the boundless power of that hand to create.

Wall Type	Fire Resistance (hours)	STC
4" (100-mm) brick	1	45
6" (150-mm) brick	2	51
8" (200-mm) brick	2–4	52
10", 12" (250-mm, 300-mm) brick	4	59
4" CMU	½–1	43–47[a]
6" CMU	1	44–51[a]
8" CMU	1–2	45–55[a]
10" CMU	3–4	46–59[a]

[a]STC ratings for concrete masonry assume paint or plaster finishes both sides.

Figure 10.21

Approximate fire resistance ratings and Sound Transmission Class (STC) ratings for some types of masonry partitions. Fire resistance of masonry construction varies with the density of the masonry units (less dense units conduct heat more slowly and can achieve higher ratings), the total mass of the wall (greater mass absorbs more heat with less rise in temperature and can achieve a higher rating), and other factors, such as whether the wall is solid or has a cavity, whether combustible members are framed into the wall, and the presence of applied finishes, such as plaster or gypsum board, that can contribute to fire resistance. STC ratings also vary with wall density, mass, and the presence of finish coatings.

Material	Strength in Tension	Strength in Compression	Modulus of Elasticity	Density
Wood (framing lumber)	270–4100 psi (1.9–28 MPa)	1400–4400 psi (9.7–31 MPa)	1,100,000–1,900,000 psi (7600–13,000 MPa)	27 pcf (430 kg/m^3)
Brick masonry (including mortar, unreinforced)	30–80 psi (0.21–0.55 MPa)	1000–4000 psi (6.9–28 MPa)	800,000–3,000,000 psi (5500–21,000 MPa)	120 pcf (1900 kg/m^3)
Structural steel	60,000 –90,000 psi (415–620 MPa)	60,000 –90,000 psi (415–620 MPa)	29,000,000 psi (200,000 MPa)	490 pcf (7800 kg/m^3)
Concrete (unreinforced)	300–700 psi 2.1–4.8 MPa	3000–6000 psi (20–40 MPa)	2,000,000–6,000,000 psi (14,000–41,000 MPa)	145 pcf (2300 kg/m^3)

FIGURE 10.22
Comparative ultimate strength properties of four common structural materials: wood, brick masonry (shaded row), steel, and concrete. Unreinforced masonry has little useful tensile strength. Wood values are for stresses parallel to the grain of the wood.

FIGURE 10.23
A detail of the porch of H. H. Richardson's First Baptist Church, Boston, built in 1871. *(Photo by Edward Allen.)*

MasterFormat Sections for Masonry Wall Construction

04 05 00	**COMMON WORK RESULTS FOR MASONRY**
04 05 19	Masonry Anchorage and Reinforcing
04 05 23.13	Masonry Control and Expansion Joints
04 05 23.16	Masonry Embedded Flashing
04 05 23.19	Masonry Cavity Drainage, Weep Holes, and Vents
04 27 00	**MULTIPLE-WYTHE UNIT MASONRY**
04 27 13	Composite Unit Masonry
04 27 23	Cavity Wall Unit Masonry
04 42 00	**STONE MASONRY**
07 11 00	**DAMPROOFING**
07 11 13	Bituminous Dampproofing
07 11 16	Cementitious Dampproofing
07 62 00	**SHEET METAL FLASHING AND TRIM**
07 65 00	**FLEXIBLE FLASHING**
32 14 00	**UNIT PAVING**
32 14 13	Precast Concrete Unit Paving
32 14 16	Brick Unit Paving
32 14 40	Stone Paving
32 14 43	Porous Unit Paving

Key Terms

composite masonry wall
cavity wall
veneer
flashing
weep hole
reglet
dampproofing
mortar deflection material
masonry loadbearing wall, masonry bearing wall
Ordinary construction
Mill construction
external flashing
internal flashing, concealed flashing, through-wall flashing
coping
counterflashing
drip edge
sheet metal flashing
self-adhered flashing
composite flashing, laminated flashing
end dam
cavity wall vent
thermal mass
exterior insulation and finish system (EIFS)
furring strip
nonmovement joint
movement joint
working joint
structure/enclosure joint
isolation joint
control joint
expansion joint
building separation joint
volume-change joint
settlement joint
seismic separation joint
efflorescence
spall
repointing
tuckpointing
clear water repellent
integral water repellent
permeable unit paving, porous unit paving

Review Questions

1. Describe how a cavity wall works and sketch its major construction features. What aspects of cavity wall construction are most critical to its success in preventing water leakage?

2. Where should flashings be installed in (or on) a masonry wall? What is the function of the flashing in each of these locations?

3. Where should weep holes be provided? Describe the function of a weep hole and indicate several ways in which it may be constructed.

4. What are the differences between Ordinary construction and Heavy Timber construction? What features of each are related to fire resistance?

5. What types of movement joints are required in a concrete or brick masonry wall? Where should these joints be located?

6. What are some ways of insulating masonry walls?

7. Why is balloon framing used rather than platform framing in Ordinary construction?

8. What precautions should be taken when constructing masonry walls in Minneapolis in the winter?

Exercises

1. What are the allowable height and floor area for a restaurant (Occupancy A-2) in a building of heavy timber Type IV-HT construction? How do these figures change if unprotected Ordinary Type III-B construction is used instead? (Assume that sprinklers are not required.) What if unprotected steel joists are substituted for the wood joists (Type II-B construction)? Or precast concrete plank floors with a 2-hour fire rating (Type I-B construction)?

2. Examine the masonry walls of some new buildings in your area. Where have movement joints been placed in these walls? What type of joint is each? Why is it placed where it is? Do you agree with this placement?

3. Look at weep holes and flashings in these same buildings. How are they detailed? Can you improve on these details?

4. Design a masonry gateway for one of the entrances to a college campus with which you are familiar. Choose whatever type of masonry you feel is appropriate and make the fullest possible use of the decorative and structural potentials of the material.

Selected References

See also the references listed in Chapters 8 and 9.

The Masonry Society. *Masonry Designers' Guide*. Boulder, CO, updated regularly.

This comprehensive design guide is based on *Building Code Requirements for Masonry Structures, ACI 530/ASCE 5/TMS 402* (discussed in this chapter) and the related *Specifications for Masonry Structures*. It also includes extensive commentary, illustrations, and design examples relating to the design and construction of masonry structures.

Websites

Advanced Building Products (flashings): www.advancedbuildingproducts.com/product-category/through-wall-flashings

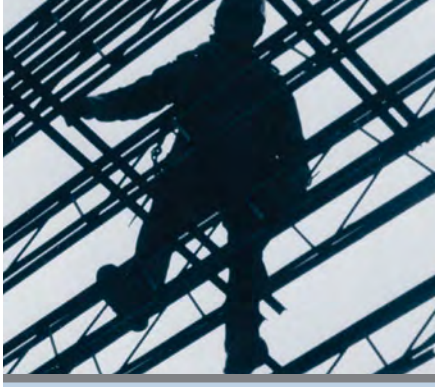
Grace Construction Products (masonry products): gcpat.com/en/solutions/masonry-hardscapes-solutions

Hohmann & Barnard Company: www.h-b.com

Mortar Net Solutions: www.mortarnet.com

The Masonry Society: masonrysociety.org

Whole Building Design Guide, Masonry Wall Systems: www.wbdg.org/guides-specifications/building-envelope-design-guide/wall–systems/masonry-wall-systems



11

Steel Frame Construction

- History
- The Material Steel
  - Steel

Preliminary Design of Steel Structures

  - Structural Steel Alloys
  - Production of Structural Shapes
  - Cast Steel
  - Cold-Worked Steel
  - Open-Web Steel Joists
- Joining Steel Members
  - Rivets
  - Bolts
  - Welding
- Details of Steel Framing
  - Steel Connections
  - Lateral Stability of the Building Frame

Seismic Force Resisting Systems

  - Shear and Moment Connections
- The Construction Process
  - The Fabricator
  - The Erector
  - Floor and Roof Decking
  - Architectural Structural Steel
- Fire Protection of Steel Framing
- Longer Spans and Higher-Capacity Columns in Steel
  - Improved Beams
  - Trusses
  - Arches
  - Tensile Structures

Fabric Structures

  - Composite Columns

Sustainability and Steel Frame Construction

- Steel and the Building Codes
- Uniqueness of Steel

Ironworkers place open-web steel joists on a frame of steel wide-flange beams as a crane lowers bundles of joists from above. *(Photo by Balthazar Korab, courtesy Vulcraft Division of Nucor.)*

Steel, strong and stiff, is a material of slender towers and soaring spans. Precise and predictable, light in proportion to its strength, it is also well suited to rapid construction, repetitive building frames, and architectural details that satisfy the eye with a clean, precise elegance. Among the metals, it is uniquely plentiful and inexpensive. If its weaknesses—vulnerability to corrosion and a loss of strength during severe building fires—are held in check by intelligent construction measures, it offers the designer possibilities that exist with no other material.

History

Prior to the beginning of the 19th century, metals had little structural role in buildings except as connecting devices. The Greeks and Romans used hidden cramps of bronze to join blocks of stone, and architects of the Renaissance countered the thrust of masonry vaults with wrought iron chains and rods. The first all-metal structure, a cast iron Iron Bridge, was built in the late 18th century in England and still stands across the Severn River more than two centuries after its construction. Cast iron, produced from iron ore in a blast furnace, and wrought iron, iron that has been purified by beating it repeatedly with a hammer, were used increasingly for framing industrial buildings in Europe and North America in the first half of the 19th century (Figure 11.1), but their usefulness was limited by the unpredictable brittleness of cast iron and the relatively high cost of wrought iron.

Until the mid-1850s, steel had been a rare and expensive material, produced only in small batches for applications such as weapons and cutlery. Plentiful, inexpensive steel first became available at that time

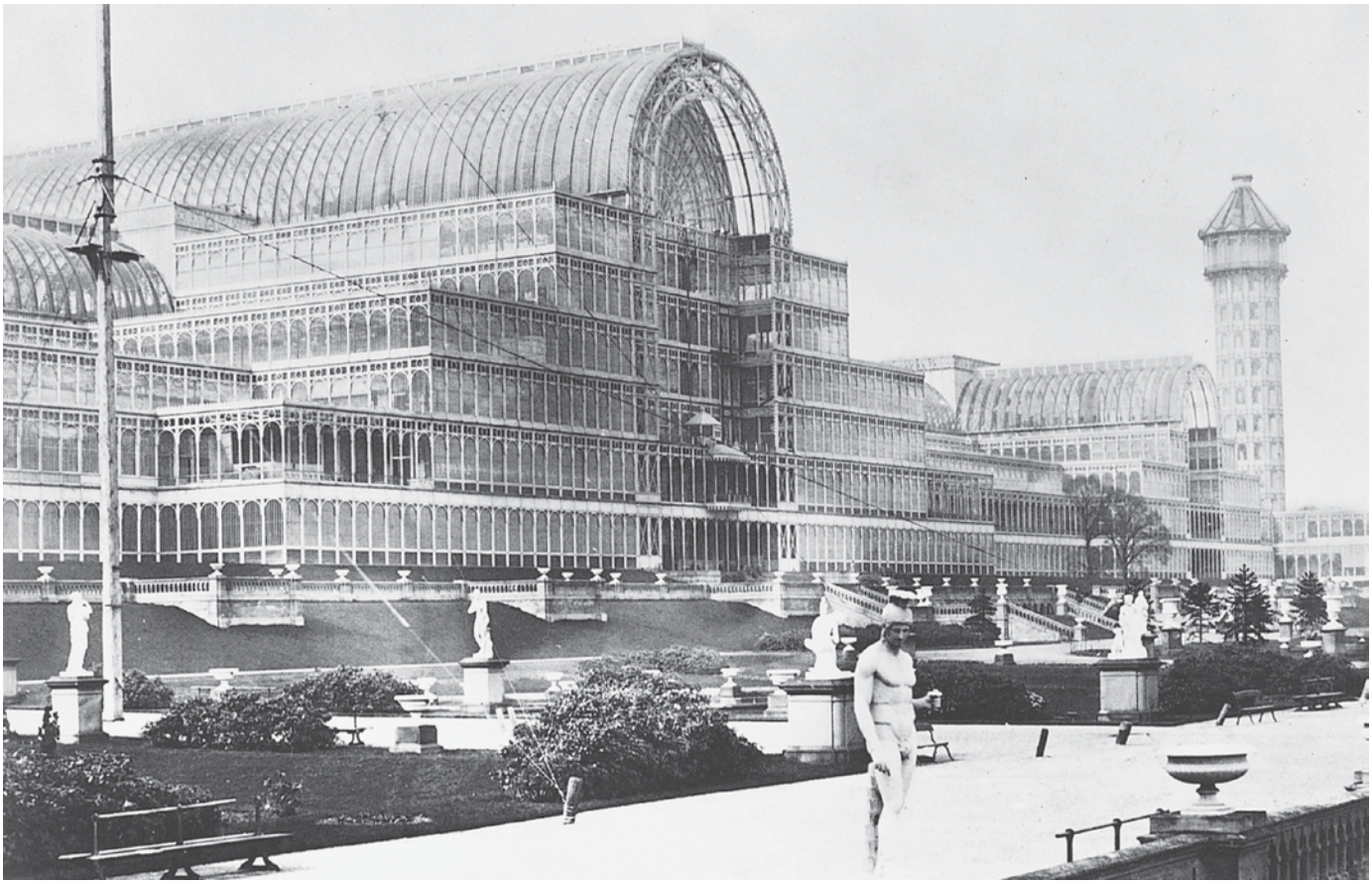


Figure 11.1
Landscape architect Joseph Paxton designed the Crystal Palace, an exposition hall of cast iron and glass, which was built in London in 1851. *(Bettmann Archive.)*

Figure 11.2
Allied Bank Plaza, designed by architect Skidmore, Owings & Merrill. *(Permission of the American Institute of Steel Construction.)*

with the introduction of the *Bessemer process*, in which air was blown into a vessel of molten iron to burn out the impurities. By this means, a large batch of iron could be made into steel in about 20 minutes, and the structural properties of the resulting metal were vastly superior to those of cast iron. Another economical steelmaking process, the *open-hearth method*, was developed in Europe in 1868 and was soon adopted in America. By 1889, when the Eiffel Tower was built of wrought iron in Paris (Figure 11.3), several steel frame skyscrapers had already been erected in the United States (Figure 11.4). A new material of construction had been born.

The Material Steel

Steel

Steel is any of a range of *alloys* of iron (iron mixed with other substances) that contain less than roughly 2 percent carbon. Ordinary structural steel, called *mild steel*, contains less than three-tenths of 1 percent carbon, plus traces of beneficial elements such as manganese and silicon, and of detrimental impurities such as phosphorus, sulfur, oxygen, and nitrogen. In contrast, ordinary *cast iron* contains 2 to 4 percent carbon and greater quantities of impurities than steel, while *wrought iron* contains even less carbon than most steel alloys. Carbon content is a crucial determinant of the properties of any *ferrous* (iron-based) *metal*: Too much carbon makes a hard but brittle metal, like cast iron, while too little produces a malleable, weaker material, like wrought iron. Thus, mild steel is an iron alloy whose properties have been optimized for structural purposes by controlling the amounts of carbon and other elements in the metal.

The gap between stone and steel-and-glass was as great as that in the evolutionary order between the crustaceans and the vertebrates.

—Lewis Mumford, *The Brown Decades*, 1955, pp. 130–131

The process of converting *iron ore* (oxides of iron extracted from the earth in mineral form) to steel begins with the *smelting* of the ore into cast iron. This is done in a *blast furnace*, which is charged with alternating layers of iron ore, *coke* (coal whose volatile constituents have been distilled out, leaving only carbon), and crushed limestone. The coke is burned by large quantities of air

Figure 11.3
Engineer Gustave Eiffel's magnificent tower of wrought iron was constructed in Paris between 1887 and 1889. *(Photo by James Austin, Cambridge, United Kingdom.)*

forced into the bottom of the furnace. This produces carbon monoxide, which reacts with the ore, reducing it to elemental iron. The limestone forms a *slag* containing various impurities that floats on top of the molten metal. But large amounts of carbon and other elements inevitably remain incorporated into the iron as well. The molten iron is drawn off at the bottom of the furnace and held in a liquid state for processing into steel (Figure 11.5).

Today, roughly one-third of North American steel is made using the *basic oxygen process* (Figure 11.6). In this method, a hollow, water-cooled lance is lowered into a container of molten iron produced from ore (as above) along with recycled steel scrap. A stream of pure oxygen at very high pressure is blown from the lance into the metal to burn off the excess carbon and impurities. A flux of lime and fluorspar is added to the metal to react with other impurities, particularly phosphorus, and forms a slag that is discarded. New metallic elements may be added to the container at the end of the process to adjust the composition of the steel as desired: Manganese gives resistance to abrasion and impact, molybdenum gives strength, vanadium imparts strength and toughness, and nickel and chromium give corrosion resistance, toughness, and stiffness. The entire process, which takes less than an hour from start to finish, is performed with the aid of careful sampling and analysis techniques to ensure the finished quality of the steel.

The greater share of structural steel produced on this continent is made from virtually 100 percent scrap steel in so-called *mini-mills*, utilizing *electric arc furnaces*. These mills are miniature only in comparison to the conventional mills that they have replaced; they are housed in enormous buildings and roll structural shapes of any size and shape. The scrap from which structural steel is made comes mostly from defunct automobiles, one mini-mill alone consuming 300,000 junk cars in an average year. Through careful metallurgical testing and control, these are recycled into top-quality steel.

Regardless of the particular steel-making process, finished steel is cast continuously into *beam blanks*, or *blooms*, very thick approximations of the desired final shape, which are then rolled into final form, as described later in this chapter.

FIGURE 11.4
The Home Insurance Company Building, designed by William LeBaron Jenney and built in Chicago in 1884, was among the earliest true skyscrapers. The steel framing was fireproofed with masonry, and the exterior masonry facings were supported on the steel frame. *(Photo by Wm. T. Barnum. Courtesy of Chicago Historical Society ICHi-18293.)*

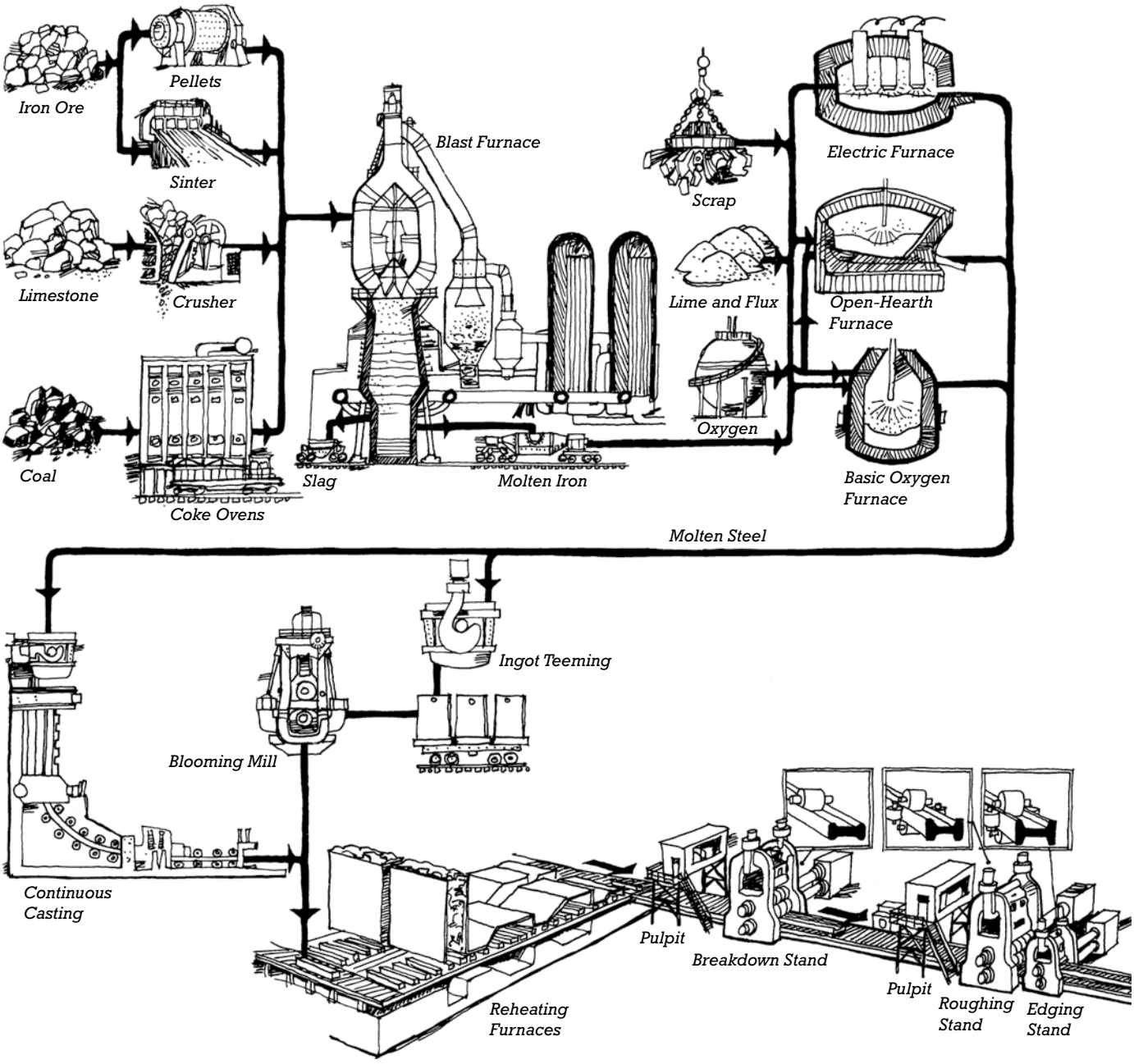


FIGURE 11.5

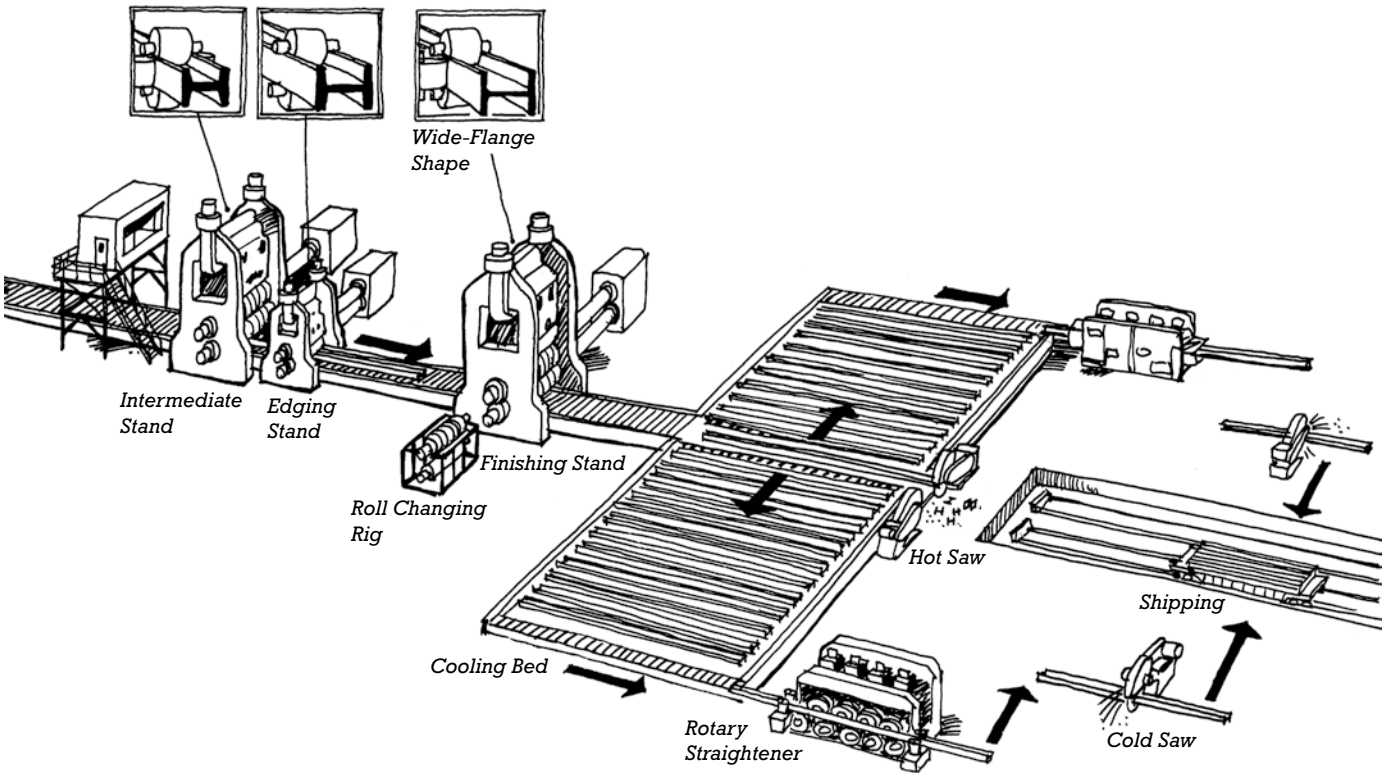
The steelmaking process, from iron ore to structural shapes. Notice particularly the steps in the evolution of a wide-flange shape as it progresses through the various stands in the rolling mill. Today, most structural steel in the United States is made from steel scrap in electric furnaces. *(Adapted from* Steelmaking Flowlines *with the permission of the American Iron & Steel Institute.)*

Preliminary Design of Steel Structures

- Estimate the depth of **corrugated steel roof decking** at 1/40 of its span. Standard depths are 1, 1½, 2, and 4 inches (25, 38, 50, and 100 mm).
- Estimate the overall depth of **corrugated steel floor decking plus concrete topping** at 1/24 of its span. Typical overall depths range from 2½ to 7 inches (65 to 180 mm).
- Estimate the depth of **open-web steel joists** at 1/20 of their span for heavily loaded floors or widely spaced joists and at 1/24 of their span for roofs, lightly loaded floors, or closely spaced joists. The spacing of joists depends on the spanning capability of the decking material. Typical joist spacings range from 2 to 10 feet (0.6–3.0 m). Standard joist depths are given elsewhere in this chapter.
- Estimate the depth of 1/20 of their span and the depth of **steel girders** at 1/20 of their span. The width of a beam or girder is usually 1/3 to ½ of its depth. For composite beams and girders, use the same ratios but apply them to the overall depth of the beam or girder, including the floor deck and concrete topping. Standard depths of steel wide-flange shapes are given elsewhere in this chapter.
- Estimate the depth of **triangular steel roof trusses** at ¼ to 1/5 of their span. For rectangular trusses, the depth is typically 1/8 to 1/12 of their span.
- To estimate the size of a **steel column**, add up the total roof and floor area supported by the column. A W8 column can support up to about 4000 square feet (370 m^2) and a W14 column 30,000 square feet (2800 m^2). Very heavy W14 shapes, which are substantially larger than 14 inches (355 mm) in dimension, can support up to 50,000–100,000 square feet (4600–9300 m^2). Steel column shapes are usually square or nearly square in proportion.

These approximations are valid only for purposes of preliminary building layout and must not be used to select final member sizes. They apply to the normal range of building occupancies such as residential, office, commercial, and institutional buildings and parking garages. For manufacturing and storage buildings, use somewhat larger members.

For more comprehensive information on preliminary selection and layout of a structural system and sizing of structural members, see Edward Allen and Joseph Iano, *The Architect's Studio Companion* (6th ed.), Hoboken, NJ, John Wiley & Sons, 2017.



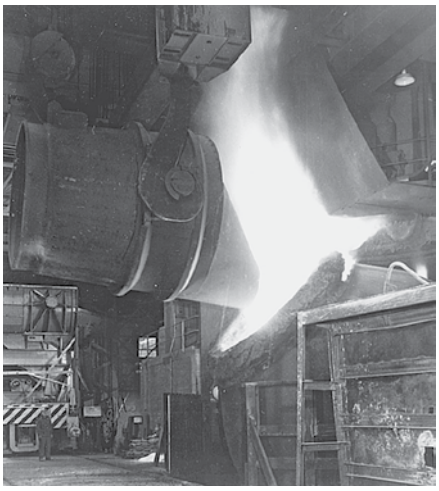


FIGURE 11.6
Molten iron is poured into a crucible to begin its conversion to steel in the basic oxygen process. *(Courtesy of U.S. Steel Corp.)*

Structural Steel Alloys

By adjusting the mix of elements used in the production of steel, its mechanical properties can be manipulated. Mild structural steel, known by its ASTM designation A36, was for many decades the predominant type used in building frames. Today's mini-mills, using scrap as their primary raw material, economically produce higher-strength types, called *high-strength, low-alloy steels*, such as ASTM A992 and A572. ASTM A992 steel, with well-defined ductile behavior (important to seismic design), is the preferred type for standard wide-flange structural shapes. ASTM A36 steel may still be specified for other common shapes such as angles, channels, plates, and bars. Or, where very high-strength components are needed, ASTM A572 steel may be used.

Where steel without any protective finish will remain exposed to exterior conditions in the completed construction, *weathering steel* (ASTM A588 for structural shapes and A606 for thin sheet) may be specified. This alloy develops a tenacious oxide coating when exposed to the atmosphere that, once formed, protects against further corrosion and eliminates the need for paint or another coating. Though used mostly for highway and bridge construction where it reduces maintenance costs, weathering steel also finds use in buildings, where the deep, warm hue of the oxide coating can be exploited for its aesthetic qualities.

With the addition of nickel and chromium to steel, various grades of *stainless steel* (ASTM A240 and A276) with even greater corrosion resistance than weathering steel—and costing significantly more than conventional structural steel—can be produced.

In some cases, the properties of steel are adjusted after the final shapes are rolled as well. For example, immediately after hot rolling, ASTM A913 steel is subjected to a process of *quenching* (rapid cooling) and then *tempering* (partial reheating) to give the steel an optimized balance of strength, toughness, and weldability characteristics.

Production of Structural Shapes

In the *structural mill* (or *breakdown mill*), the beam blank is reheated as necessary and then passed through a succession of rollers that squeeze the metal into progressively more refined approximations of the desired shape and size (Figure 11.7). The finished shape exits from the last set of rollers as a continuous length that is cut into shorter segments by a *hot saw* (Figure 11.8). These segments are cooled on a *cooling bed* (Figure 11.9),

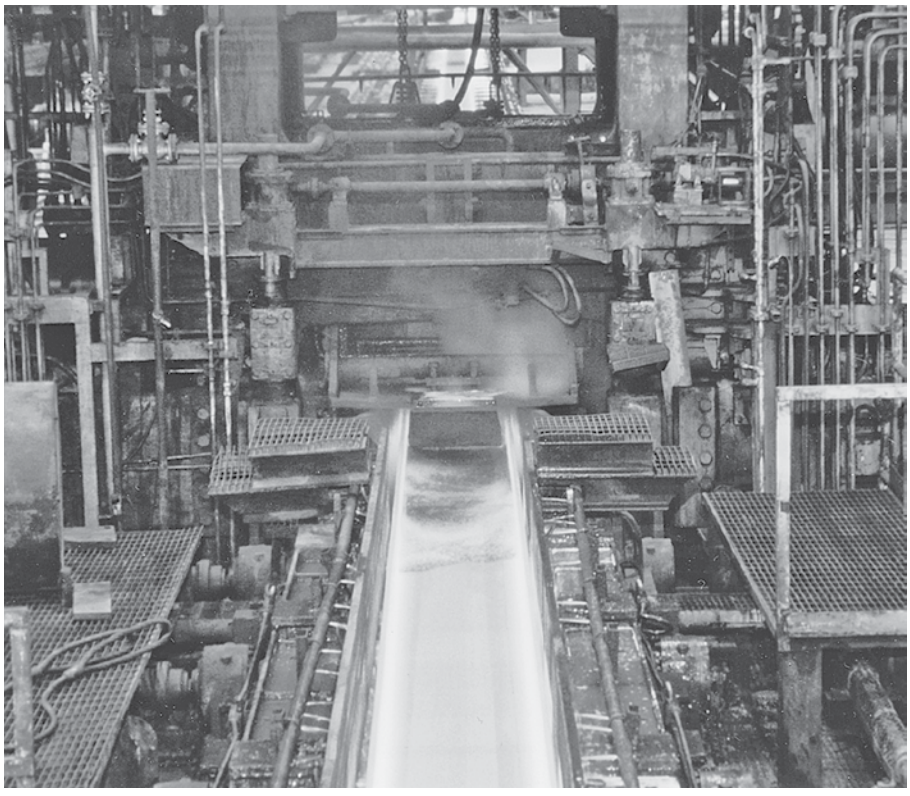


FIGURE 11.7
A glowing steel wide-flange shape emerges from the rolls of the finishing stand of the rolling mill. *(Photo by Mike Engestrom, courtesy of Nucor-Yamato Steel Company.)*

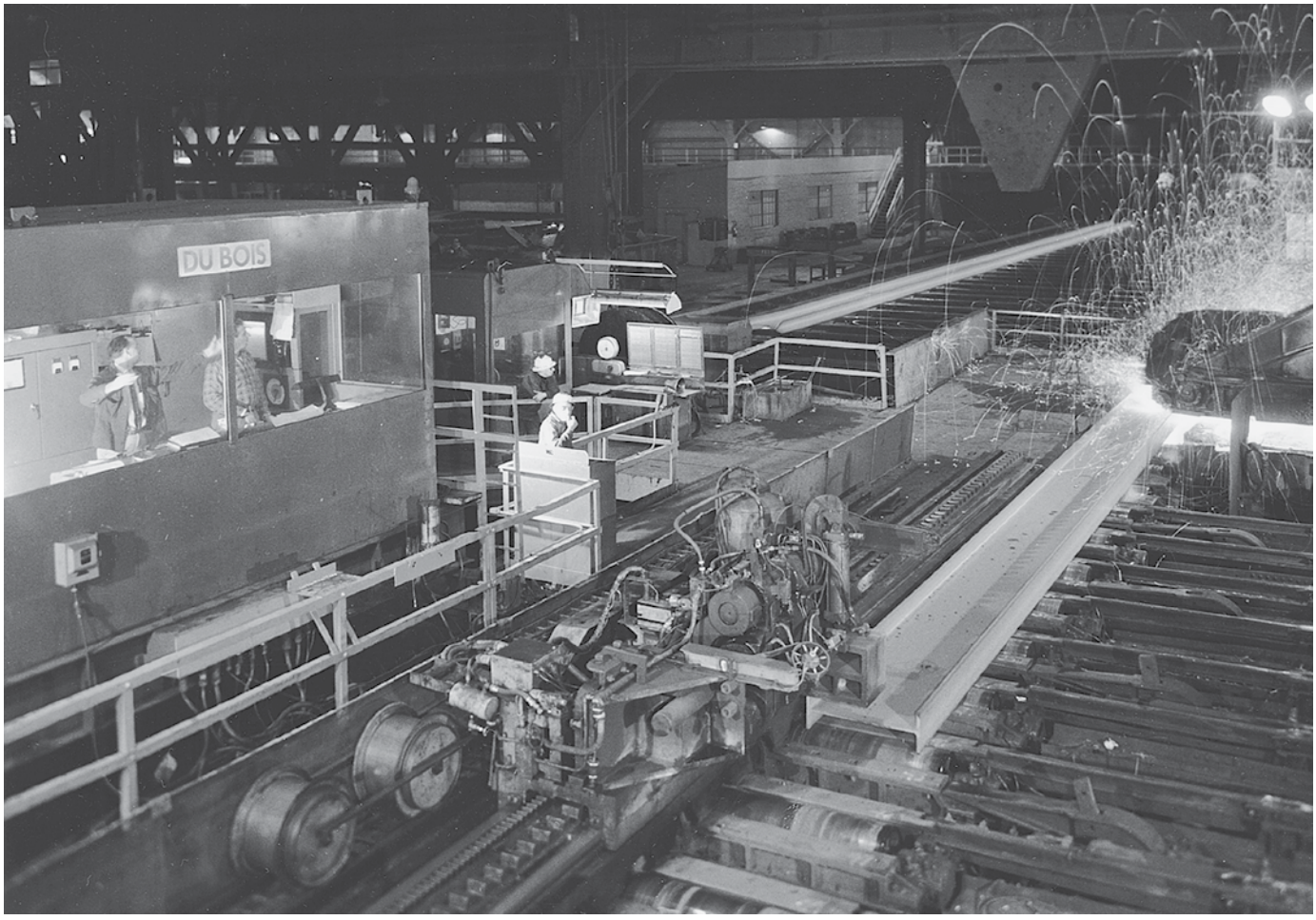


FIGURE 11.8
A hot saw cuts pieces of wide-flange stock from a continuous length that has just emerged from the finishing stand in the background. Workers in the booth control the process. *(Courtesy of U.S. Steel Corp.)*

FIGURE 11.9
Wide-flange shapes are inspected for quality on the cooling bed. *(Photo by Mike Engestrom, courtesy of Nucor-Yamato Steel Company.)*

and then a *roller straightener* corrects any residual crookedness. Finally, each piece is cut to length and labeled with its shape designation and the number of the batch of steel from which it was produced. Later, when the piece is shipped to a fabricator, it will be accompanied by a certificate that gives the chemical analysis of that particular batch, as evidence that the steel meets standard specifications.

The roller spacings in the structural mill are adjustable. By varying the spacings between them, families of related size shapes with the same nominal dimensions are produced (Figure 11.10). This provides the architect and structural engineer with a finely graduated selection of shapes from which to select for each structural member in a building, thereby avoiding waste through the specification of shapes that are larger than required.

Wide-flange shapes are used for most beams and columns, having many decades ago superseded the older *American Standard* (*I-beam*) shapes. American Standard beams are less efficient structurally than wide-flange beams. The roller arrangement used to form them is incapable of increasing the thickness of the

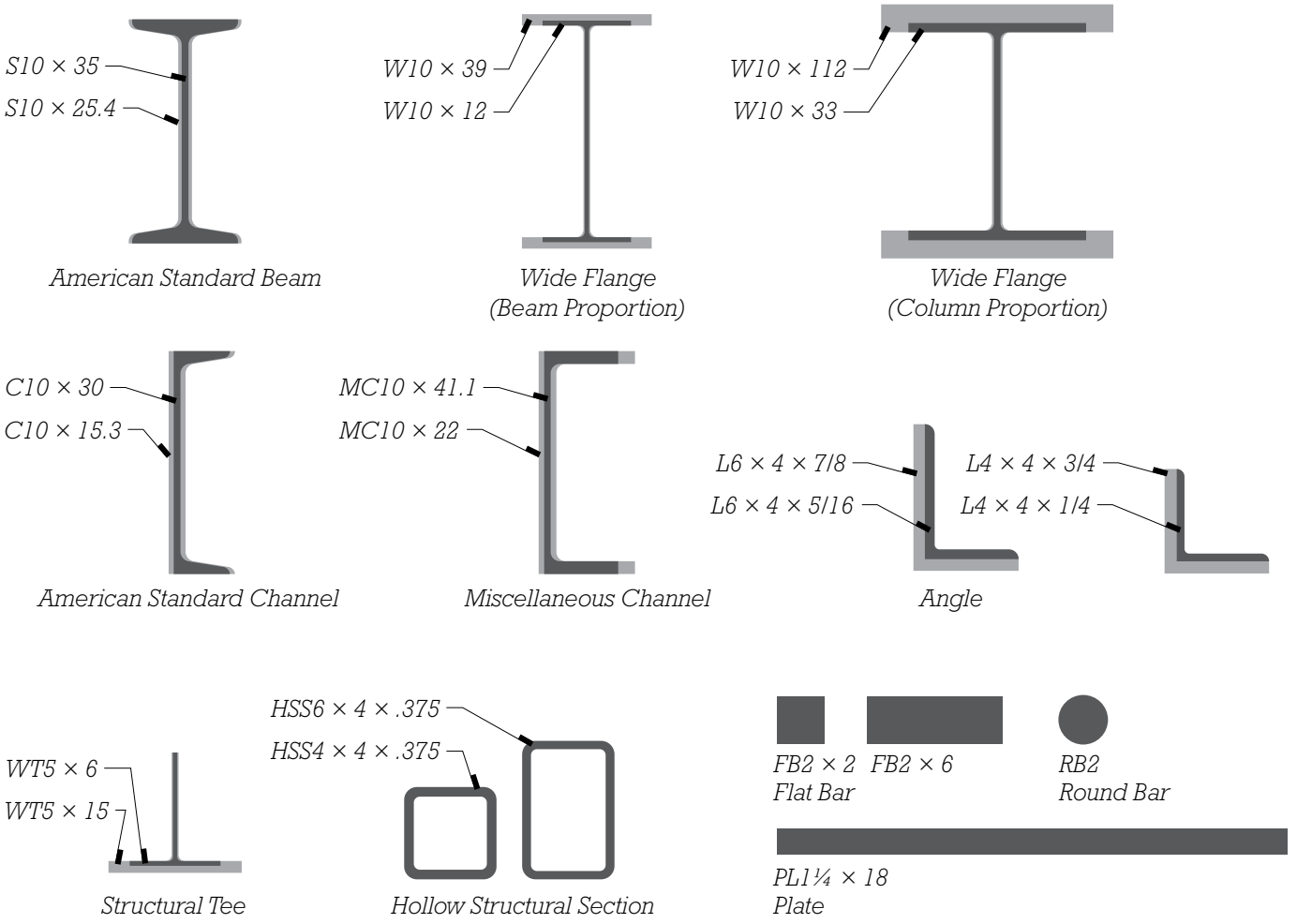


FIGURE 11.10

Standard structural steel shapes. Where two shapes are superimposed, they illustrate different weights of the same section, produced by varying the spacing of the rollers in the structural mill. Structural steel shapes and their basic properties are defined in ASTM A6. Bars are round, rectangular, and hexagonal solid shapes generally not greater than 8 inches (203 mm) in any cross-sectional dimension. Wider solid shapes are called plate or sheet, depending on their thickness in relation to their width. Plate is thicker than sheet.

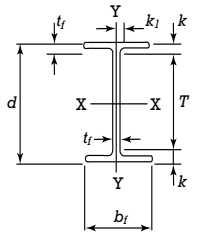
outer flanges without also adding steel to the middle web, where it does little to increase the load-carrying capacity of the member. Wide-flange shapes are available in a vast range of sizes and weights. The smallest available depth in the United States is nominally 4 inches (100 mm), and the largest is 44 inches (1117 mm). Weights per linear foot of member range from 8.5 to 655 pounds (13 to 975 kg/m), the latter for a nominal 14-inch (360-mm) shape with flanges roughly 3½ inches (89 mm) thick. Some producers construct heavier wide-flange sections by welding together flange and web plates rather than rolling, a procedure that is also used for producing very deep, long-span plate girders.

Structural shapes are identified using a standard nomenclature, beginning with a letter designation for the shape, followed by one or more size, thickness, or weight designations. Beam, column, channel, and T shapes are identified with shape, nominal depth, and weight. For example, an MC10 × 22 is a miscellaneous channel shape (MC), nominally 10 inches deep, and weighing 22 pounds per foot. Angles, hollow structural sections, bars, and plates are identified by shape, size, and thickness (but not weight) (Figure 11.11).

Wide flanges are manufactured in two basic proportions: tall and narrow for beams and squarish for columns. The nomenclature for wide-flange shapes begins with the letter W. Thus, a W12 × 26 is a wide-flange shape nominally 12 inches (305 mm) deep that weighs 26 pounds per foot of length (38.5 kg/m). More information about this shape is contained in tables (or databases) of dimensions and properties published by the American Institute of Steel Construction (Figure 11.12): Its actual depth is 12.2 inches (310 mm), and its flanges are 6.49 inches (165 mm) wide. These relatively tall proportions indicate that the shape is intended mainly for use as a beam or girder and not as a column. Reading across the table column by column, the designer can learn everything there is to know about this section, from its thicknesses and the radii of its fillets to various quantities that are useful in computing its structural behavior. At the upper end of the portion of the table dealing with 12-inch (305-mm) wide flanges, we find shapes weighing up to 336 pounds per foot (501 kg/m), with actual depths of

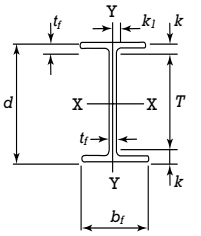
Shape	Example of Designation	Explanation	Range of Available Sizes
Wide flange	W21 × 83	Nominal depth × weight	4"–44" *102 mm–1118 mm* in 4" increments
American Standard beam	S18 × 70	Nominal depth × weight	3"–24" *76 mm–610 mm*
Channel	MC10 × 36	Nominal depth × weight	6"–18" *152 mm–457 mm*
American Standard channel	C6 × 13	Nominal depth × weight	3"–15" *76 mm–381 mm*
Structural tee	WT13.5 × 47	Nominal depth × weight	WTs are split from wide-flange shapes. See the W beam sizes listed above and divide by 2 for available WT depths.
Angle	L4 × 3 × ⅜	Length of each leg followed by thickness	Legs: 2"–8" (*51–203 mm*) Thickness: ⅛" to 1⅛" (*3–29 mm*)
HSS Square, Rectangular, or Elliptical	HSS10 × 8 × ½	Nominal depth and width followed by wall thickness	Depth and width: 1"–48" (*25–1219 mm*) Wall thickness: ⅛"–⅝" (*3–16 mm*)
HSS Round	HSS8 × ½	Nominal diameter followed by wall thickness	Diameter: 1.66"–20" (*42–508 mm*) Wall thickness: 0.109"–0.625" (*2.8–16 mm*)

FIGURE 11.11
Commonly used steel shapes and sizes.



W SHAPES Dimensions

Designation	Area A	Depth d		Web			Flange				Distance		
				Thickness t_w		$\frac{t_w}{2}$	Width b_f		Thickness t_f		T	k	k_1
	In.^{2}	In.		In.		In.	In.		In.		In.	In.	In.
W 12×336	98.8	16.82	$16\frac{7}{8}$	1.775	$1\frac{3}{4}$	$\frac{7}{8}$	13.385	$13\frac{3}{8}$	2.955	$2\frac{15}{16}$	$9\frac{1}{2}$	$3\frac{11}{16}$	$1\frac{1}{2}$
×305	89.6	16.32	$16\frac{3}{8}$	1.625	$1\frac{5}{8}$	$\frac{13}{16}$	13.235	$13\frac{1}{4}$	2.705	$2\frac{11}{16}$	$9\frac{1}{2}$	$3\frac{7}{16}$	$1\frac{7}{16}$
×279	81.9	15.85	$15\frac{7}{8}$	1.530	$1\frac{1}{2}$	$\frac{3}{4}$	13.140	$13\frac{1}{8}$	2.470	$2\frac{1}{2}$	$9\frac{1}{2}$	$3\frac{3}{16}$	$1\frac{3}{8}$
×252	74.1	15.41	$15\frac{3}{8}$	1.395	$1\frac{3}{8}$	$\frac{11}{16}$	13.005	13	2.250	$2\frac{1}{4}$	$9\frac{1}{2}$	$2\frac{15}{16}$	$1\frac{5}{16}$
×230	67.7	15.05	15	1.285	$1\frac{5}{16}$	$\frac{11}{16}$	12.895	$12\frac{7}{8}$	2.070	$2\frac{1}{16}$	$9\frac{1}{2}$	$2\frac{3}{4}$	$1\frac{1}{4}$
×210	61.8	14.71	$14\frac{3}{4}$	1.180	$1\frac{3}{16}$	$\frac{5}{8}$	12.790	$12\frac{3}{4}$	1.900	$1\frac{7}{8}$	$9\frac{1}{2}$	$2\frac{5}{8}$	$1\frac{1}{4}$
×190	55.8	14.38	$14\frac{3}{8}$	1.060	$1\frac{1}{16}$	$\frac{9}{16}$	12.670	$12\frac{5}{8}$	1.735	$1\frac{3}{4}$	$9\frac{1}{2}$	$2\frac{7}{16}$	$1\frac{3}{16}$
×170	50.0	14.03	14	0.960	$\frac{15}{16}$	$\frac{1}{2}$	12.570	$12\frac{5}{8}$	1.560	$1\frac{9}{16}$	$9\frac{1}{2}$	$2\frac{1}{4}$	$1\frac{1}{8}$
×152	44.7	13.71	$13\frac{3}{4}$	0.870	$\frac{7}{8}$	$\frac{7}{16}$	12.480	$12\frac{1}{2}$	1.400	$1\frac{3}{8}$	$9\frac{1}{2}$	$2\frac{1}{8}$	$1\frac{1}{16}$
×136	39.9	13.41	$13\frac{3}{8}$	0.790	$\frac{13}{16}$	$\frac{7}{16}$	12.400	$12\frac{3}{8}$	1.250	$1\frac{1}{4}$	$9\frac{1}{2}$	$1\frac{15}{16}$	1
×120	35.3	13.12	$13\frac{1}{8}$	0.710	$\frac{11}{16}$	$\frac{3}{8}$	12.320	$12\frac{3}{8}$	1.105	$1\frac{1}{8}$	$9\frac{1}{2}$	$1\frac{13}{16}$	1
×106	31.2	12.89	$12\frac{7}{8}$	0.610	$\frac{5}{8}$	$\frac{5}{16}$	12.220	$12\frac{1}{4}$	0.990	1	$9\frac{1}{2}$	$1\frac{11}{16}$	$\frac{15}{16}$
× 96	28.2	12.71	$12\frac{3}{4}$	0.550	$\frac{9}{16}$	$\frac{5}{16}$	12.160	$12\frac{1}{8}$	0.900	$\frac{7}{8}$	$9\frac{1}{2}$	$1\frac{5}{8}$	$\frac{7}{8}$
× 87	25.6	12.53	$12\frac{1}{2}$	0.515	$\frac{1}{2}$	$\frac{1}{4}$	12.125	$12\frac{1}{8}$	0.810	$\frac{13}{16}$	$9\frac{1}{2}$	$1\frac{1}{2}$	$\frac{7}{8}$
× 79	23.2	12.38	$12\frac{3}{8}$	0.470	$\frac{1}{2}$	$\frac{1}{4}$	12.080	$12\frac{1}{8}$	0.735	$\frac{3}{4}$	$9\frac{1}{2}$	$1\frac{7}{16}$	$\frac{7}{8}$
× 72	21.1	12.25	$12\frac{1}{4}$	0.430	$\frac{7}{16}$	$\frac{1}{4}$	12.040	12	0.670	$\frac{11}{16}$	$9\frac{1}{2}$	$1\frac{3}{8}$	$\frac{7}{8}$
× 65	19.1	12.12	$12\frac{1}{8}$	0.390	$\frac{3}{8}$	$\frac{3}{16}$	12.000	12	0.605	$\frac{5}{8}$	$9\frac{1}{2}$	$1\frac{5}{16}$	$\frac{13}{16}$
W 12× 58	17.0	12.19	$12\frac{1}{4}$	0.360	$\frac{3}{8}$	$\frac{3}{16}$	10.010	10	0.640	$\frac{5}{8}$	$9\frac{1}{2}$	$1\frac{3}{8}$	$\frac{13}{16}$
× 53	15.6	12.06	12	0.345	$\frac{3}{8}$	$\frac{3}{16}$	9.995	10	0.575	$\frac{9}{16}$	$9\frac{1}{2}$	$1\frac{1}{4}$	$\frac{13}{16}$
W 12× 50	14.7	12.19	$12\frac{1}{4}$	0.370	$\frac{3}{8}$	$\frac{3}{16}$	8.080	$8\frac{1}{8}$	0.640	$\frac{5}{8}$	$9\frac{1}{2}$	$1\frac{3}{8}$	$\frac{13}{16}$
× 45	13.2	12.06	12	0.335	$\frac{5}{16}$	$\frac{3}{16}$	8.045	8	0.575	$\frac{9}{16}$	$9\frac{1}{2}$	$1\frac{1}{4}$	$\frac{13}{16}$
× 40	11.8	11.94	12	0.295	$\frac{5}{16}$	$\frac{3}{16}$	8.005	8	0.515	$\frac{1}{2}$	$9\frac{1}{2}$	$1\frac{1}{4}$	$\frac{3}{4}$
W 12× 35	10.3	12.50	$12\frac{1}{2}$	0.300	$\frac{5}{16}$	$\frac{3}{16}$	6.560	$6\frac{1}{2}$	0.520	$\frac{1}{2}$	$10\frac{1}{2}$	1	$\frac{9}{16}$
× 30	8.79	12.34	$12\frac{3}{8}$	0.260	$\frac{1}{4}$	$\frac{1}{8}$	6.520	$6\frac{1}{2}$	0.440	$\frac{7}{16}$	$10\frac{1}{2}$	$\frac{15}{16}$	$\frac{1}{2}$
× 26	7.65	12.22	$12\frac{1}{4}$	0.230	$\frac{1}{4}$	$\frac{1}{8}$	6.490	$6\frac{1}{2}$	0.380	$\frac{3}{8}$	$10\frac{1}{2}$	$\frac{7}{8}$	$\frac{1}{2}$
W 12× 22	6.48	12.31	$12\frac{1}{4}$	0.260	$\frac{1}{4}$	$\frac{1}{8}$	4.030	4	0.425	$\frac{7}{16}$	$10\frac{1}{2}$	$\frac{7}{8}$	$\frac{1}{2}$
× 19	5.57	12.16	$12\frac{1}{8}$	0.235	$\frac{1}{4}$	$\frac{1}{8}$	4.005	4	0.350	$\frac{3}{8}$	$10\frac{1}{2}$	$\frac{13}{16}$	$\frac{1}{2}$
× 16	4.71	11.99	12	0.220	$\frac{1}{4}$	$\frac{1}{8}$	3.990	4	0.265	$\frac{1}{4}$	$10\frac{1}{2}$	$\frac{3}{4}$	$\frac{1}{2}$
× 14	4.16	11.91	$11\frac{7}{8}$	0.200	$\frac{3}{16}$	$\frac{1}{8}$	3.970	4	0.225	$\frac{1}{4}$	$10\frac{1}{2}$	$\frac{11}{16}$	$\frac{1}{2}$



W SHAPES Properties

Nominal Wt per Ft.	Compact Section Criteria				rT	$\frac{d}{A_f}$	Elastic Properties						Torsional constant J	Plastic Modulus	
							Axis X-X			Axis Y-Y					
	$\frac{b_f}{2t_f}$	F_y	$\frac{d}{t_w}$	F_y			I	S	r	I	S	r		Z_x	Z_y
Lb.		Ksi		Ksi	In.		In.^{4}	In.^{3}	In.	In.^{4}	In.^{3}	In.	In.^{4}	In.^{3}	In.^{3}
336	2.3	—	9.5	—	3.71	0.43	4060	483	6.41	1190	177	3.47	243	603	274
305	2.4	—	10.0	—	3.67	0.46	3550	435	6.29	1050	159	3.42	185	537	244
279	2.7	—	10.4	—	3.64	0.49	3110	393	6.16	937	143	3.38	143	481	220
252	2.9	—	11.0	—	3.59	0.53	2720	353	6.06	828	127	3.34	108	428	196
230	3.1	—	11.7	—	3.56	0.56	2420	321	5.97	742	115	3.31	83.8	386	177
210	3.4	—	12.5	—	3.53	0.61	2140	292	5.89	664	104	3.28	64.7	348	159
290	3.7	—	13.6	—	3.50	0.65	1890	263	5.82	589	93.0	3.25	48.8	311	143
170	4.0	—	14.6	—	3.47	0.72	1650	235	5.74	517	82.3	3.22	35.6	275	126
152	4.5	—	15.8	—	3.44	0.79	1430	209	5.66	454	72.8	3.19	25.8	243	111
136	5.0	—	17.0	—	3.41	0.87	1240	186	5.58	398	64.2	3.16	18.5	214	98.0
120	5.6	—	18.5	—	3.38	0.96	1070	163	5.51	345	56.0	3.13	12.9	286	85.4
106	6.2	—	21.1	—	3.36	1.07	933	145	5.47	301	49.3	3.11	9.13	164	75.1
96	6.8	—	23.1	—	3.34	1.16	833	131	5.44	270	44.4	3.09	6.86	147	67.5
87	7.5	—	24.3	—	3.32	1.28	740	118	5.38	241	39.7	3.07	5.10	132	60.4
79	8.2	62.6	26.3	—	3.31	1.39	662	107	5.34	216	35.8	3.05	3.84	119	64.4
72	9.0	52.3	28.5	—	3.29	1.52	597	97.4	5.31	195	32.8	3.04	2.93	108	49.2
65	9.9	43.0	31.1	—	3.28	1.67	533	87.9	5.28	174	29.1	3.02	2.18	96.8	44.1
58	7.8	—	33.9	57.6	3.72	1.90	475	78.0	5.28	107	21.4	2.51	2.10	86.4	32.5
53	8.7	55.9	35.0	54.1	2.71	2.10	425	70.6	5.23	95.8	19.2	2.41	1.58	77.9	29.1
50	6.3	—	32.9	60.9	2.17	2.36	394	64.7	5.18	56.3	13.9	1.96	1.78	72.4	21.4
45	7.0	—	36.0	51.0	2.15	2.61	350	58.1	5.15	50.0	12.4	1.94	1.31	64.7	19.0
40	7.8	—	40.5	40.3	2.14	2.90	310	51.9	5.13	44.1	11.0	1.93	0.95	57.5	16.8
35	6.3	—	41.7	38.0	2.74	3.66	285	45.6	5.25	24.5	7.47	1.54	0.74	51.2	11.5
30	7.4	—	47.5	29.3	2.73	4.30	238	38.6	5.21	20.3	6.24	1.52	0.46	43.1	9.56
26	8.5	57.9	53.1	23.4	2.72	4.95	204	33.4	5.17	17.3	5.34	1.51	0.30	37.2	8.17
22	4.7	—	47.3	29.5	1.02	7.19	156	25.4	4.91	4.66	2.31	0.847	0.29	29.3	3.66
19	5.7	—	51.7	24.7	1.00	8.67	130	21.3	4.82	3.76	1.88	0.822	0.18	24.7	2.98
16	7.5	—	54.5	22.2	0.96	11.3	103	17.1	4.67	2.82	1.41	0.773	0.10	20.1	2.26
14	8.8	54.3	59.6	18.6	0.95	13.3	88.6	14.9	4.62	2.36	1.19	0.753	0.07	17.4	1.90

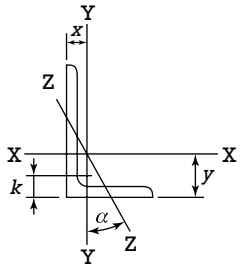
FIGURE 11.12

A portion of the table of dimensions and properties of wide-flange shapes from the *Steel Construction Manual* of the American Institute of Steel Construction. This is information is also available in tabulated spreadsheet and database formats. One inch equals 25.4 mm. *(Permission of the American Institute of Steel Construction.)*

almost 17 inches (432 mm). These heavier shapes have flanges nearly as wide as the shapes are deep, making them more suitable for use as columns. U.S. producers manufacture steel shapes only in conventional units of measurement, that is, inches and pounds. In other parts of the world, a standard range of metric sizes is used. The United States has adopted a soft conversion to metric sizes, merely tabulating metric dimensions for shapes that are produced in conventional units.

Steel *angles* (Figure 11.13) are extremely versatile. They can be

ANGLES
Equal legs and unequal legs
Properties for designing



Size and Thickness		*k*	Weight Per Foot	Area	AXIS X-X				AXIS Y-Y				AXIS Z-Z	
					I	*S*	*r*	*y*	*I*	*S*	*r*	*x*	*r*	Tan α
In.		In.	Lb.	In.^{2}	In.^{4}	In.^{3}	In.	In.	In.^{4}	In.^{3}	In.	In.	In.	
L 4 x3 x	5/8	1 1/16	**13.6**	**3.98**	**6.03**	**2.30**	**1.23**	**1.37**	**2.87**	**1.35**	**0.849**	**0.871**	**0.637**	**0.534**
	1/2	15/16	11.1	3.25	5.05	1.89	1.25	1.33	2.42	1.12	0.864	0.827	0.639	0.543
	7/16	**7/8**	**9.8**	**2.87**	**4.52**	**1.68**	**1.25**	**1.30**	**2.18**	**0.992**	**0.871**	**0.804**	**0.641**	**0.547**
	3/8	13/18	8.5	2.48	3.96	1.46	1.26	1.28	1.92	0.866	0.879	0.782	0.644	0.551
	5/16	3/4	7.2	2.09	3.38	1.23	1.27	1.26	1.65	0.734	0.887	0.759	0.647	0.554
	1/4	11/16	5.8	1.69	2.77	1.00	1.28	1.24	1.36	0.599	0.896	0.736	0.651	0.558
L 3 1/2 x3 1/2 x	1/2	7/8	**11.1**	**3.25**	**3.64**	**1.49**	**1.06**	**1.06**	**3.64**	**1.49**	**1.06**	**1.06**	**0.683**	**1.000**
	7/16	**13/16**	**9.8**	**2.87**	**3.26**	**1.32**	**1.07**	**1.04**	**3.26**	**1.32**	**1.07**	**1.04**	**0.684**	**1.000**
	3/8	3/4	8.5	2.48	2.87	1.15	1.07	1.01	2.87	1.15	1.07	1.01	0.687	1.000
	5/6	11/16	7.2	2.09	2.45	0.976	1.08	0.990	2.45	0.976	1.08	0.990	0.690	1.000
	1/4	5/8	5.8	1.69	2.01	0.794	1.09	0.968	2.01	0.794	1.09	0.968	0.694	1.000
L 3 1/2 x3 x	1/2	15/16	**10.2**	**3.00**	**3.45**	**1.45**	**1.07**	**1.13**	**2.33**	**1.10**	**0.881**	**0.875**	**0.621**	**0.714**
	7/16	**7/8**	**9.1**	**2.65**	**3.10**	**1.29**	**1.08**	**1.10**	**2.09**	**0.975**	**0.889**	**0.853**	**0.622**	**0.718**
	3/8	13/16	7.9	2.30	2.72	1.13	1.09	1.08	1.85	0.851	0.897	0.830	0.625	0.721
	5/16	3/4	6.6	1.93	2.33	0.954	1.10	1.06	1.58	0.722	0.905	0.808	0.627	0.724
	1/4	11/16	5.4	1.56	1.91	0.776	1.11	1.04	1.30	0.589	0.914	0.785	0.631	0.727
L 3 1/2 x3 1/2 x	1/2	15/16	**9.4**	**2.75**	**3.24**	**1.41**	**1.09**	**1.20**	**1.36**	**0.760**	**0.704**	**0.705**	**0.534**	**0.486**
	7/16	**7/8**	**8.3**	**2.43**	**2.91**	**1.26**	**1.09**	**1.18**	**1.23**	**0.677**	**0.711**	**0.682**	**0.535**	**0.491**
	3/8	13/16	7.2	2.11	2.56	1.09	1.10	1.16	1.09	0.592	0.719	0.660	0.537	0.496
	5/16	3/4	6.1	1.78	2.19	0.927	1.11	1.14	0.939	0.504	0.727	0.637	0.540	0.501
	1/4	11/16	4.9	1.44	1.80	0.755	1.12	1.11	0.777	0.412	0.735	0.614	0.544	0.506
L 3 x3 x	1/2	13/16	9.4	2.75	2.22	1.07	0.898	0.932	2.22	1.07	0.898	0.932	0.584	1.000
	7/16	**3/4**	**8.3**	**2.43**	**1.99**	**0.954**	**0.905**	**0.910**	**1.99**	**0.954**	**0.905**	**0.910**	**0.585**	**1.000**
	3/8	11/16	7.2	2.11	1.76	0.833	0.913	0.888	1.76	0.833	0.913	0.888	0.587	1.000
	5/16	5/8	6.1	1.78	1.51	0.707	0.922	0.865	1.51	0.707	0.922	0.865	0.589	1.000
	1/4	9/16	4.9	1.44	1.24	0.577	0.930	0.842	1.24	0.577	0.930	0.842	0.592	1.000
	3/16	1/2	3.71	1.09	0.962	0.441	0.939	0.820	0.962	0.441	0.939	0.820	0.596	1.000

Angles in shaded rows may not be readily available. Availability is subject to rolling accumulation and geographical location, and should be checked with material suppliers.

FIGURE 11.13

A portion of the table of dimensions and properties of angle shapes from the *Steel Construction Manual* of the American Institute of Steel Construction. One inch equals 24.5 mm. *(Permission of the American Institute of Steel Construction.)*

used for very short beams supporting small loads and are frequently found playing this role as lintels spanning door and window openings in masonry construction. In steel frame buildings, their primary role is in connecting wide-flange beams, girders, and columns, as we will see shortly. They also find use as diagonal braces in steel frames and as members of steel trusses, where they are paired back to back to connect conveniently to flat *gusset plates* at the joints of the truss (Figure 11.79). *Channels* are also used as truss members and bracing, and for short beams, lintels, and stringers in steel stairs. *Tees*, *plates*, *bars*, and *sheets* all have their various roles in a steel frame building, as shown in the diagrams that accompany this text.

Cast Steel

Although the vast majority of structural steel is produced as rolled shapes, structural shapes can also be produced as *cast steel*, that is, by pouring molten steel into molds and allowing the steel to cool. Although steel castings are, pound for pound, more expensive than rolled steel shapes, they have other advantages: Because cast parts are produced in small quantities, they can economically utilize specialized steel alloys selected on the basis of a part's unique requirements. Because they are cast in discrete molds rather than formed through a continuous rolling process, cast steel parts can be nonuniform in section, they can readily incorporate curves or complex geometries, and their shapes can be carefully tailored to the particular requirements of the part. Cast steel is especially well suited to the production of custom-shaped connections for steel structures that are stronger, lighter, and more attractive than possible with those fabricated from conventional rolled steel.

Cold-Worked Steel

The mechanical properties and shapes of steel members can also be modified by *cold working* (*cold forming*), that is, by rolling, bending, or stretching at room temperature. Cold working causes the steel to gain considerable strength through a realignment of its crystalline structure. Thin steel sheet is formed into lightweight C-shaped sections used to frame interior partitions and exterior walls of larger buildings and floor structures of smaller buildings (see Chapter 12). Steel sheet stock is also rolled into corrugated configurations utilized as floor and roof decking in steel-framed structures (Figures 11.59 through 11.61).

Heavier sheet or plate stock may be cold-formed into square, rectangular, round, and elliptical hollow shapes that are then welded along the longitudinal seam to form *hollow structural sections* (*HSSs*) (Figure 11.10). Also called structural tubing, they are often used for columns (Figure 11.14) and for members of welded steel trusses and space trusses. Their hollow shape makes them especially suitable for members that are subjected to torsional (twisting) stresses or to buckling associated with compressive loads.

Wide-flange shapes are generally too large to be cold-rolled, but cold rolling is used to produce small-section steel rods and components for open-web joists, where the higher strength can be utilized to good advantage. Steel is also cold-drawn through dies to produce the very-high-strength wires used in wire ropes, bridge cables, and concrete prestressing strands.

Open-Web Steel Joists

Among the many structural steel products fabricated from hot- and cold-rolled shapes, one of the most common is the *open-web steel joist (OWSJ)*, a mass-produced truss used in closely spaced arrays to support floor and roof decks (Figure 11.14). According to Steel Joist Institute (SJI) specifications, open-web steel joists are produced in four series: K series joists are for spans up to 60 feet (18 m) and range in depth from 10 to 30 inches (250 to 760 mm). Longer-span LH and DLH series joists are available in depths up to 120 inches (3048 mm) and can span up to 240 feet (73 m). CJ composite joists are designed for composite floor construction, explained later in this chapter.

Most buildings that use open-web steel joists utilize K series joists that are less than 2 feet (600 mm) deep to achieve spans of up to 40 feet (13 m). The spacings between joists commonly range from 2 to 10 feet (0.6 to 3 m), depending on the magnitude of the applied loads and the spanning capability of the decking. Often, wider joist spacings are more economical: Fewer joists and connections are needed, and the thicker slabs required help to dampen floor vibrations.

Joist girders are similar to open-web steel joists, but are designed specifically to carry other joists. They range in depth from 20 to 120 inches (508 to 3048 mm) and can span up to 120 feet (36 m). They are used in place of wide-flange beams or girders where their greater depth is not objectionable.

FIGURE 11.14
Open-web steel floor and roof joists are supported on wide-flange beams and square HSS columns. The heavy, diagonally braced frames in the far right corner of the image are part of the lateral force resisting system, explained later in this chapter. They will be incorporated into the enclosure around an exit stair to be installed in that location. *(Photo by Joseph Iano.)*

Joining Steel Members

Rivets

Steel shapes can be joined into a building frame by riveting, bolting, or welding. A *rivet* is a steel fastener consisting of a cylindrical body and a formed head. It is brought to a white heat in a forge, inserted while hot through holes in the members to be joined, and hot-worked with a pneumatic hammer to produce a second head opposite the first (Figure 11.15). As the rivet cools, it shrinks, clamping the joined pieces together and forming a tight joint. Riveting was for many decades the predominant fastening technique used in steel frame buildings, but it has been completely replaced in contemporary construction by the less labor-intensive techniques of bolting and welding.

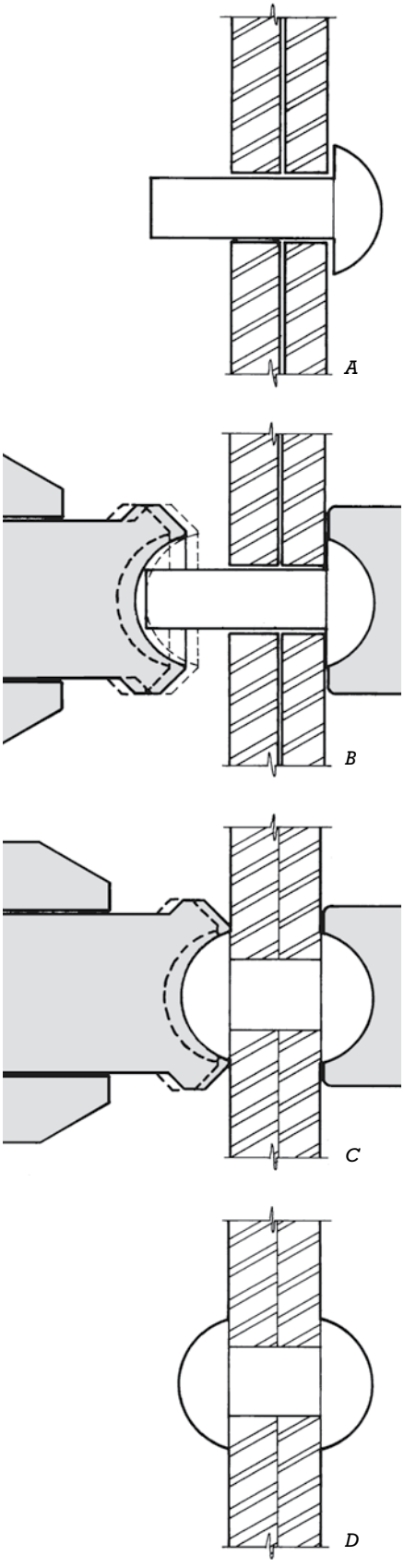


FIGURE 11.15
How riveted connections are made. (*A*) A hot steel rivet is inserted through holes in the two members to be joined. (*B, C*) Its head is placed in the cup-shaped depression of a heavy, hand-held hammer. A pneumatic hammer drives a rivet set repeatedly against the body of the rivet to form the second head. (*D*) The rivet shrinks as it cools, drawing the members tightly together.

Bolts

Structural steel members may be connected with *high-strength bolts*. These fastener types (ASTM F3125 and F3111) are heat treated during manufacturing to develop tensile strengths many times greater than ordinary *carbon steel bolts*. Carbon steel bolts (also called unfinished or common bolts) find only limited use in structural steel framing, such as in the fastening of minor framing elements or temporary connections.

The manner in which a bolted structural steel connection derives its strength depends on how the bolts are installed. In a *bearing-type connection*, bolts need only be installed to a *snug-tight* condition. In this case, movement between the joined members is resisted by the bolts themselves as the sides of the bolt holes in the connected members bear against the bodies of the bolts. In a *slip-critical* (or *friction-type*) *connection*, bolts are *preloaded* (tightened during installation) to such an extent that friction between the adjoining faces of the steel members (the *faying surfaces*) resists movement between the members. Under normal load conditions, bolts in bearing-type connections are stressed primarily in shear, while those in slip-critical connections are stressed in tension.

When a bearing-type connection is first loaded, a slight slippage of the joint occurs as the sides of the bolt holes in the joined members achieve full bearing against the bodies of the bolts. In contrast, a slip-critical connection will reach its full design capacity with virtually no initial slippage. For this reason, only slip-critical connections are used where the small changes in alignment that can occur with bearing-type connections could be detrimental to the performance of a structure. For example, column splices and beam-to-column connections in tall buildings must be designed as slip-critical, as must connections that experience load reversals.

In a typical connection, bolts are inserted into holes 1/16 inch (2 mm) larger than the diameter of the bolt. Often, hardened steel washers are inserted under one or both ends of the fastener. For example, washers are required with slotted or oversized holes to ensure that the bolt head and nut have adequate contact with the surfaces of the joined members. When installing preloaded bolts, washers may be required to prevent *galling* (tearing) of the surfaces of the joined members. Many bolt tension verification methods, discussed later in this section, also require washers under at least one end of the bolt to ensure consistent tensioning results.

Bolts are usually tightened using a pneumatic or electric *impact wrench* (Figure 11.16). In a bearing-type connection, the amount of tension in the bolts is not critical. In a slip-critical connection, bolts must be tightened reliably to at least 70 percent of their ultimate tensile strength.

An important step in the assembly of slip-critical connections is verifying that the necessary tension has been achieved in each bolt. This can be accomplished in any of several ways. In the *turn-of-nut method*, each bolt is tightened snug then turned a specified additional fraction of a turn. Depending on bolt length, bolt alloy, and other factors, the additional tightening required will range from one-third of a turn to a full turn.

In another method, a *load indicator washer*, also called a *direct tension indicator (DTI)*, is placed under the head or nut of the bolt. As the bolt is tightened, protrusions on the washer are progressively flattened in proportion to the tension in the bolt (Figure 11.17). Inspection for proper bolt tension then becomes a relatively simple matter of inserting a thin metal strip of known thickness, called a feeler gauge, to determine whether the washer has flattened sufficiently to indicate the required tension. Load indicator washers are also manufactured with tiny dye capsules attached to the washer. When the protrusions on the washer flatten sufficiently, the capsules squirt a

Figure 11.16
An ironworker tightens high-strength bolts with a pneumatic impact wrench. *(Courtesy of Bethlehem Steel Corporation.)*

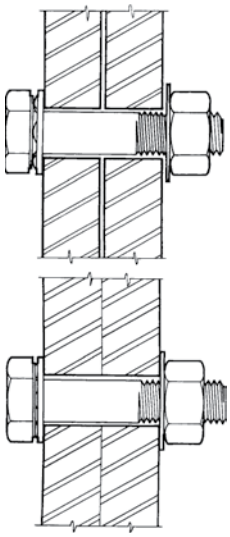


Figure 11.17
***Top*: An untightened high-strength bolt with a load indicator washer under the head. *Bottom*: The bolt and washer after tightening; notice that the protrusions on the load indicator washer have flattened.**

highly visible dye onto the surface of the washer, making it easy to visually confirm that adequate bolt tension has been achieved.

Less frequently used to verify bolt tension is the *calibrated wrench method*, in which a special torque control wrench is used to tighten the bolts. The torque setting of the wrench is calibrated for the particular size and type of fasteners being installed so as to achieve the required bolt tension. A washer under the turned end of the bolt minimizes friction and ensures a consistent correlation between the tightening force applied and the tension achieved in the bolt.

Yet another method of bolt tension verification employs *tension-control bolts*. These have protruding splined ends that extend beyond the threaded portion of the body of the bolt (Figure 11.18). The nut is tightened by a special power-driven *shear wrench* that grips both the nut and the splined end simultaneously, turning one against the other. The bolt is formed in such a way that when the required torque has been reached, the splined end twists off (Figure 11.19). Verification of adequate bolt tensioning in installed bolts then requires nothing more than visually checking for the absence of splines. Another advantage of this fastener type is that it is installed by a single worker, unlike conventional bolts, which require a second worker with a wrench to prevent the opposite end of the bolt assembly from turning during tightening.

An alternative to the high-strength bolt is the *lockpin and collar fastener*, or *swedge bolt*, a boltlike steel pin with annular rings that relies on a steel collar in lieu of a conventional nut to hold the pin. The swedge bolt is installed using a special power tool to hold the pin under high tension while cold forming (swaging, a crimping-like action) the collar around its end to complete the connection. As the installation process is completed, the tail of the lockpin breaks off, furnishing visual evidence that the necessary tension has been achieved in the fastener. Like the tension-control bolt, the swedge bolt can be installed by a single worker.

Welding

Welding offers a unique and valuable capability to the structural designer: It can join the members of a steel frame as if they were a monolithic whole. Welded connections, properly designed and executed, are stronger than the members they join. Although it is possible to achieve this

Figure 11.18
A splined tension-control bolt. *(Courtesy of LeJeune Bolt Company.)*

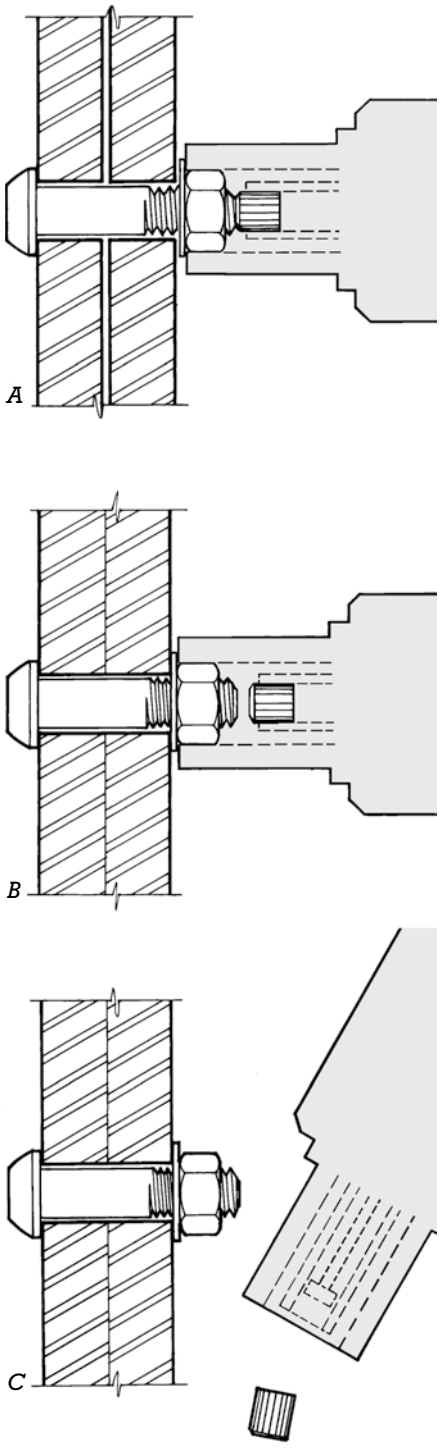


Figure 11.19
Tightening a tension-control bolt. (*A*) The wrench holds both the nut and the splined body of the bolt and turns them against one another to tighten the bolt. (*B*) When the required torque has been achieved, the splined end twists off in the wrench. (*C*) A plunger inside the wrench discharges the splined end into a container. *(Courtesy of LeJeune Bolt Company.)*

same performance with high-strength bolted connections, such connections are often cumbersome compared to equivalent welded joints. Bolting, however, has its own advantages: It is quick and easy for field connections that need only resist shearing forces, and it can be accomplished under conditions of adverse weather or difficult physical access that would make welding impossible. Often welding and bolting are combined in the same connections to take advantage of the unique qualities of each: Welding may be used in the fabricator's shop for its inherent economies and in the field for its structural continuity, whereas bolting is often employed in the simpler field connections and to hold connections in alignment prior to welding. The choice of bolting, welding, or combinations of the two may also be influenced by considerations of the fabricator's and erector's equipment and expertise, availability of electric power, weather conditions, and locale.

Electric arc welding is conceptually simple. An electrical potential is established between the steel pieces to be joined and a metal *electrode* held either by a machine or by a person. When the electrode is held close to the seam between the steel members, a continuous electric arc is established that generates sufficient heat to melt both a localized area of the steel members and the tip of the electrode (Figure 11.20). The molten steel from the electrode merges with that of the members to form a single puddle. The electrode is drawn slowly along the seam, leaving behind a continuous bead of metal that cools and solidifies to form a continuous connection between the members. For small members, a single pass of the electrode may suffice to make the connection. For larger members, a number of passes are made, building up a weld of the required depth.

In practice, welding is a complex science. The metallurgy of the structural steel and the welding electrodes must be properly matched. Voltage, amperage, and polarity of the electric current are selected to achieve the right heat and penetration for the weld. Air must be kept away from the electric arc to prevent rapid oxidation of the liquid steel; this is accomplished in simple welding processes either by a thick coating on the electrode that melts to create a liquid and gaseous shield around the arc or by a core of vaporizing flux in a tubular steel electrode. It may also be done by means of a continuous flow of inert gas around the arc, or with a dry flux that is heaped over the end of the electrode as it moves across the work.

The required thickness and length of each weld are calculated to match the forces that must be transmitted between the members, and are indicated on fabrication drawings using standardized *weld symbols* (Figure 11.21). For deep welds, such as the full-penetration welds shown in Figure 11.22, the edges of the members are beveled to create a groove that permits access of the electrode to the full thickness of the piece. Small strips of steel called *backup bars*, or *backing bars*, are welded beneath the groove before the actual weld is begun to prevent the molten metal from flowing out the bottom of the groove. The weld then is deposited in a number of passes of the electrode until the groove is fully filled. In some cases, *runoff bars* are required at the ends of a groove weld to facilitate the formation of a full thickness of weld metal at the edges of the member (Figure 11.45).

Structural welding practices and standards are governed by the American Welding Society's AWS D1.1 Structural Welding Code. Workers who do structural welding are methodically trained and periodically

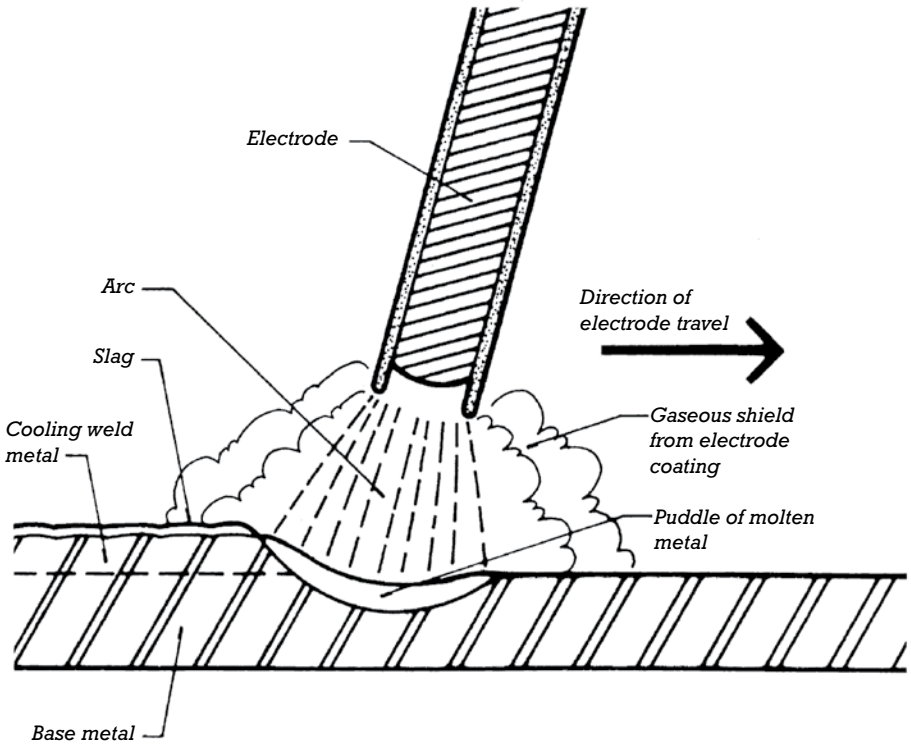


FIGURE 11.20
Close-up diagram of the electric arc welding process.

tested to ensure that they have the required level of skill and knowledge. And building codes require that, when welds are completed, they are inspected to make sure that they are of the required size and quality. Welds that play a role in a building's seismic force–resisting system are held to especially high standards due to the special demands put on these connections during seismic events. And where connections are deemed especially important to the overall stability of the building structure, welds may be designated as *demand critical*. Demand-critical welds are subject to the highest standards and quality control.

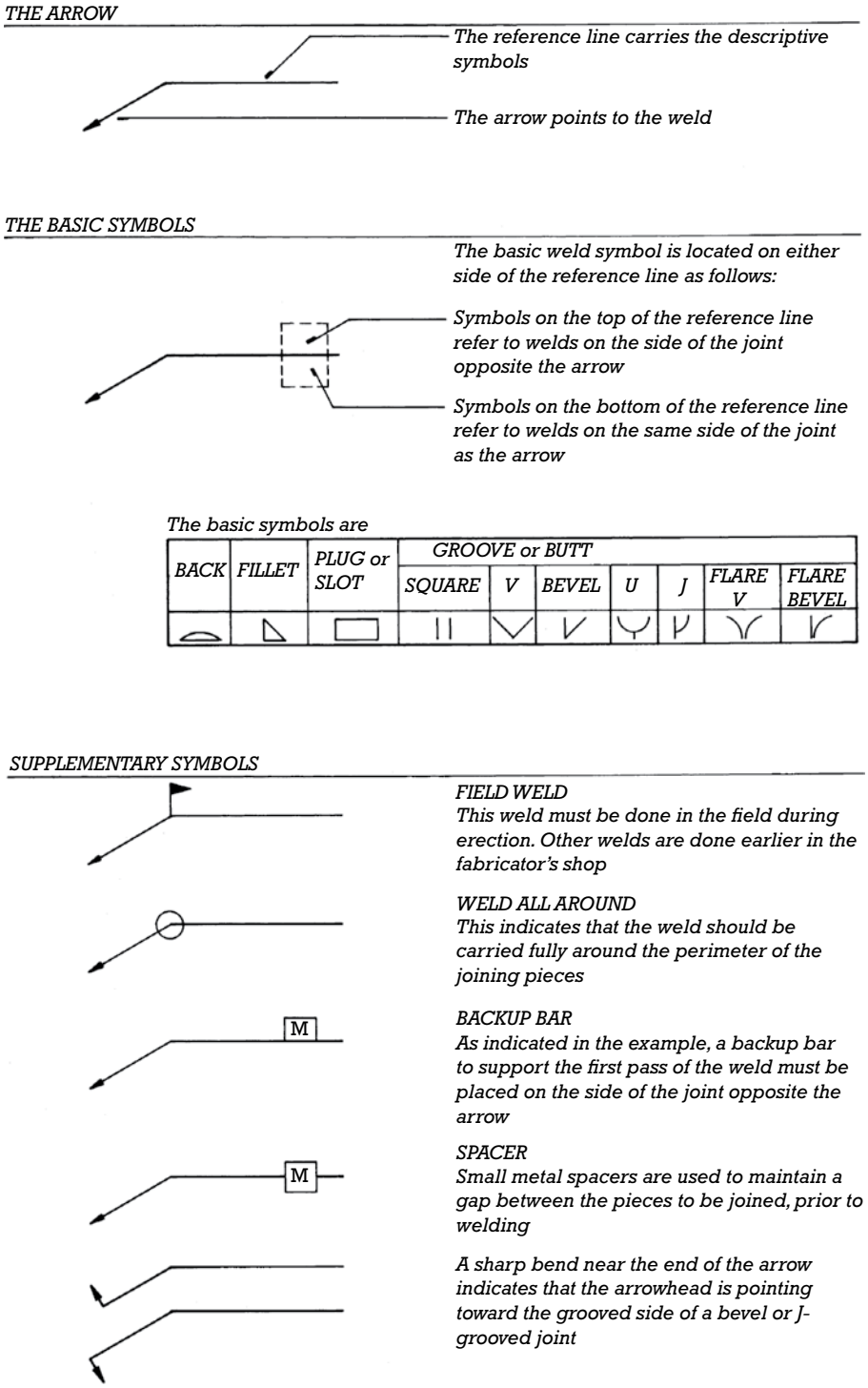


FIGURE 11.21
Standard weld symbols, as used on steel connection detail drawings.

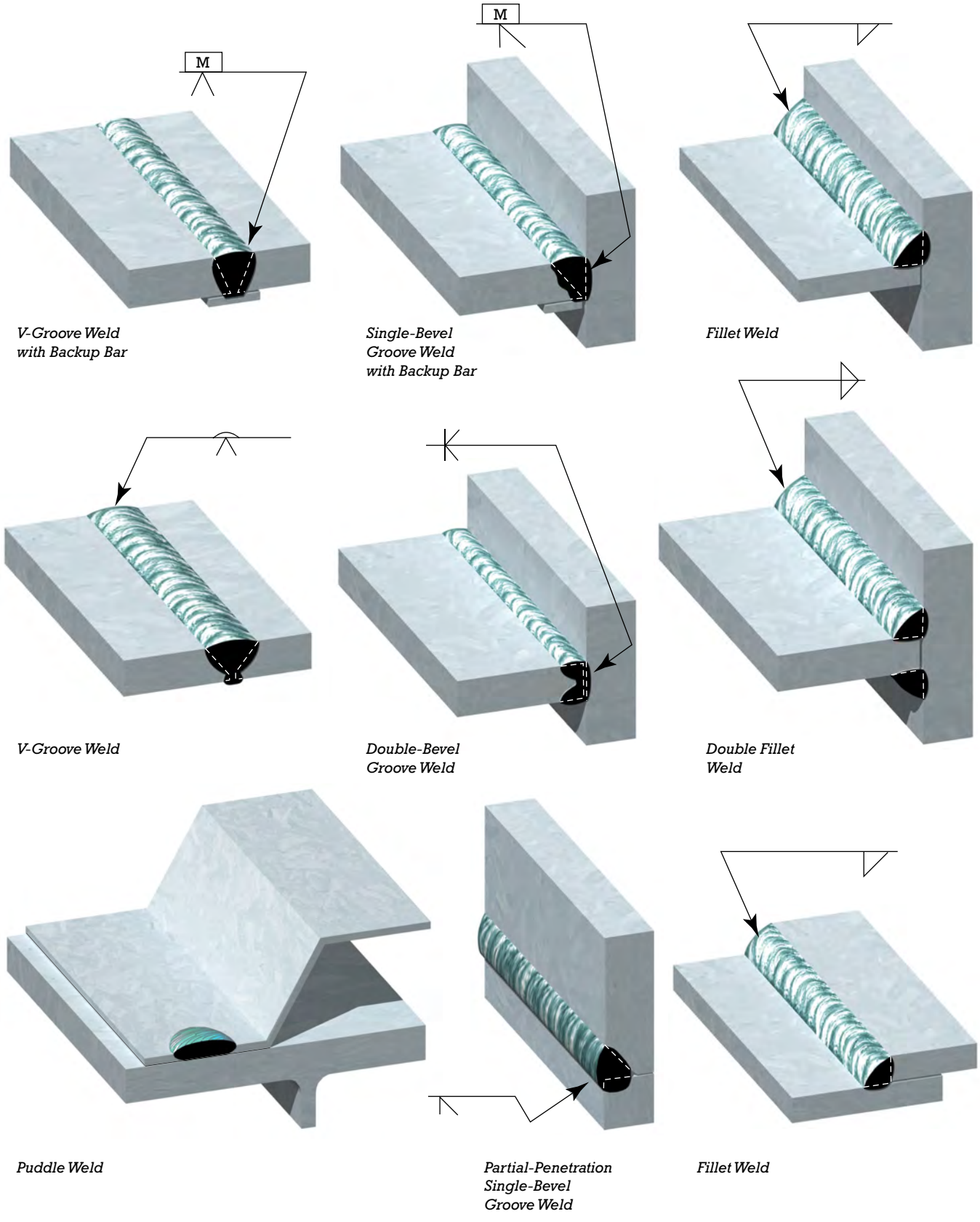


FIGURE 11.22

Typical welds used in steel frame construction. Fillet welds are the most economical because they require no advance preparation of the joint, but full-penetration groove welds are stronger. The standard symbols used here are explained in Figure 11.21.

Details of Steel Framing

Steel Connections

Most steel frame connections use angles, plates, or tees as transitional elements between the members being connected. A simple bolted beam-to-column-flange connection requires two angles and a number of bolts (Figures 11.24 through 11.26). The angles are cut to length, and the holes are made in all the components prior to assembly. The angles are usually bolted to the web of the beam in the fabricator's shop. The bolts through the flange of the column are added as the beam is erected on the construction site. This type of connection, which joins only the web of the beam, but not the flanges, to the column acts as a *shear connection*. It is capable of transmitting vertical forces (*shear*) between the beam and column. However, because it does not connect the beam flanges to the column, it is of no value in transmitting bending forces (*bending moment*) from one to the other.

To produce a *moment connection*, one capable of transmitting bending forces between a beam and column, it is necessary to also connect the beam flanges across the joint, most commonly by means of *full-penetration groove welds* (Figures 11.27 and 11.28). *Stiffener plates* are also frequently installed inside the flanges of the column to better distribute these forces into the body of the column.

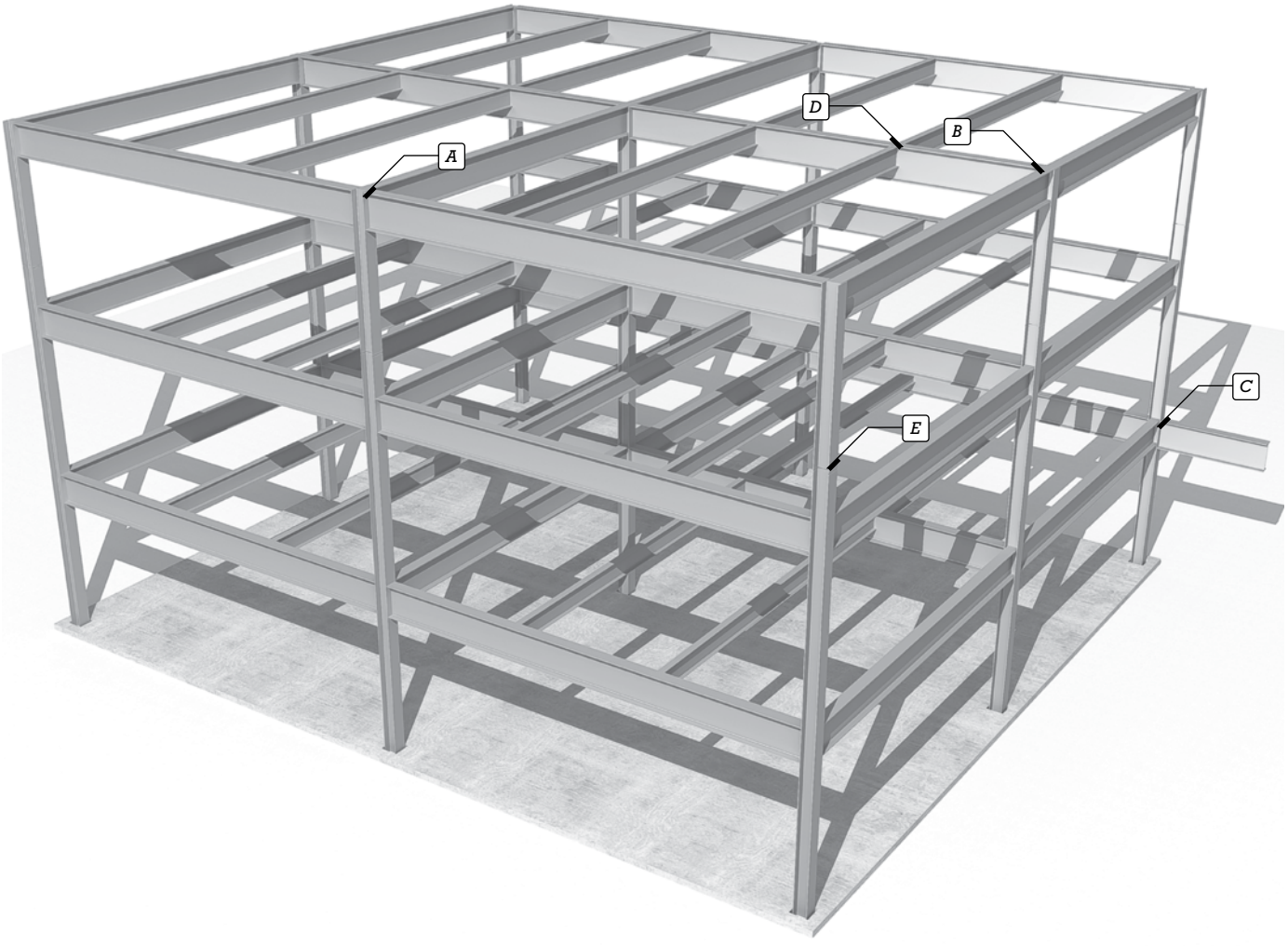


Figure 11.23
A simple steel building frame. The letters are keyed to the connection details in the figures that follow.

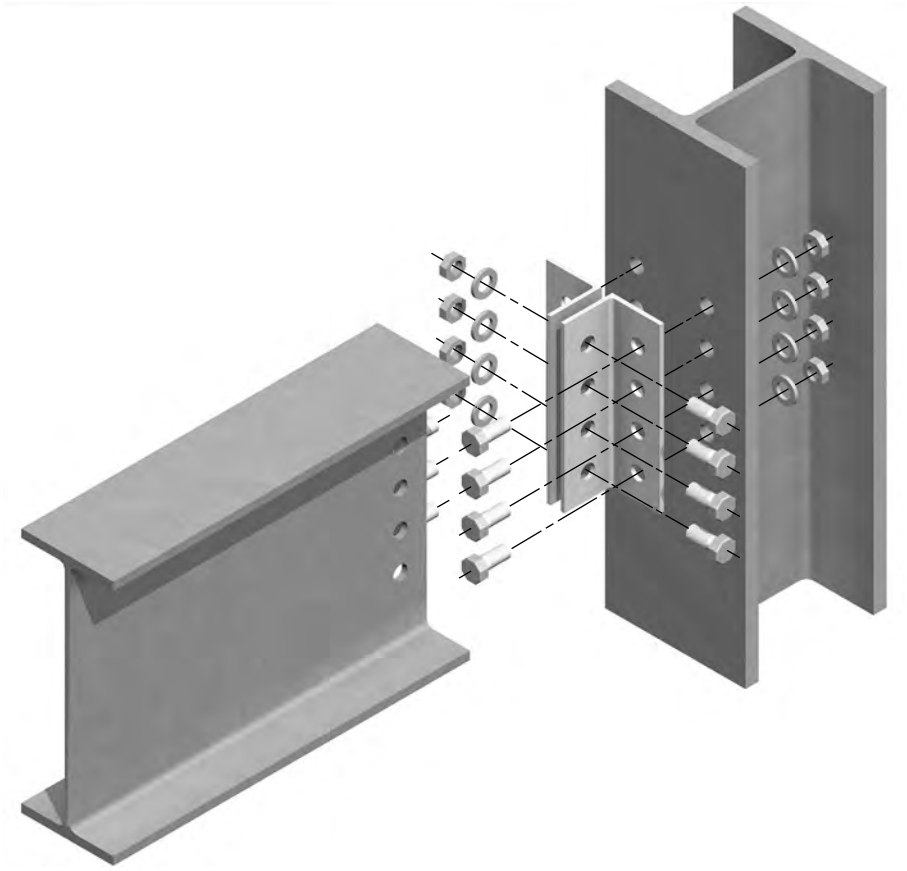


FIGURE 11.24
Exploded and assembled views of a bolted beam-to-column-flange connection, *A* on the frame shown in Figure 11.23. The size of the angles and the number and size of the bolts are determined by the magnitude of the load that the connection must transmit from the beam to the column.

Interactive Exercise

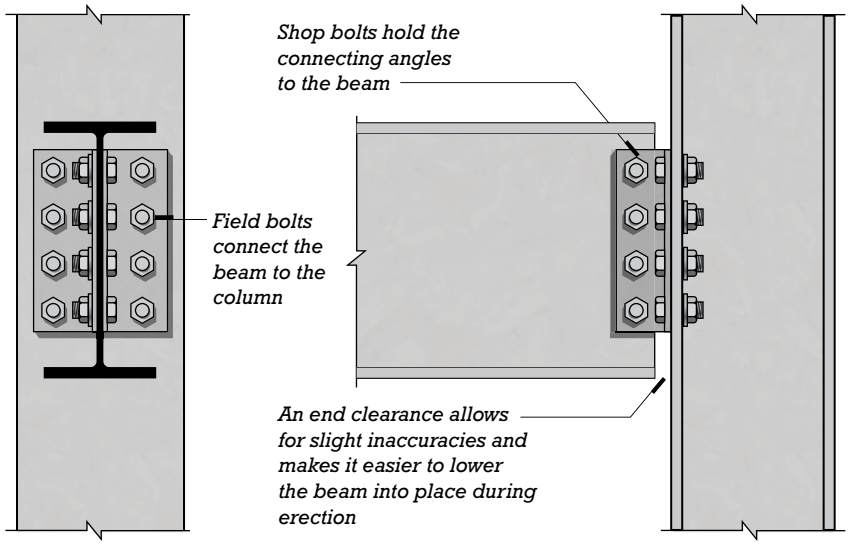


FIGURE 11.25
Two elevation views of the bolted beam-to-column-flange connection shown in Figure 11.24. This is a shear connection (AISC simple connection) and not a moment connection, because the flanges of the beam are not rigidly connected to the column. This type of shear connection, in which the beam is connected to the column by angles, plates, or tees fastened to the web of the beam, is also called a *framed connection.* Alternatively, shear connections can be seated, as illustrated in Figure 11.31.

FIGURE 11.26
A pictorial view of a framed, bolted beam-to-column-flange shear connection.

FIGURE 11.27
A welded moment connection (AISC fully restrained) for joining a beam to a column flange. This is the type of connection that would be used instead of the shear connection at location *A* in Figure 11.23 if a moment connection were required. The bolts hold the beam in place for welding and also provide shear resistance. Small rectangular backup bars are welded beneath the end of each beam flange to prevent the welding arc from burning through. A clearance hole is cut from the top of the beam web to permit the backup bar to pass through. A similar clearance hole at the bottom of the beam web allows the bottom flange to be welded entirely from above for greater convenience. The groove welds develop the full strength of the flanges of the beam, allowing the connection to transmit moments between the beam and the column. If the column flanges are not stiff enough to accept the moments from the beam, stiffener plates are welded between the column flanges, as shown here. The flanges of the beam are cut to a dog-bone configuration to create a zone of the beam that is slightly weaker in bending than the welded portion of the connection. During a severe earthquake, the beam will deform plastically in this zone while protecting the welds against the possibility of a brittle failure.

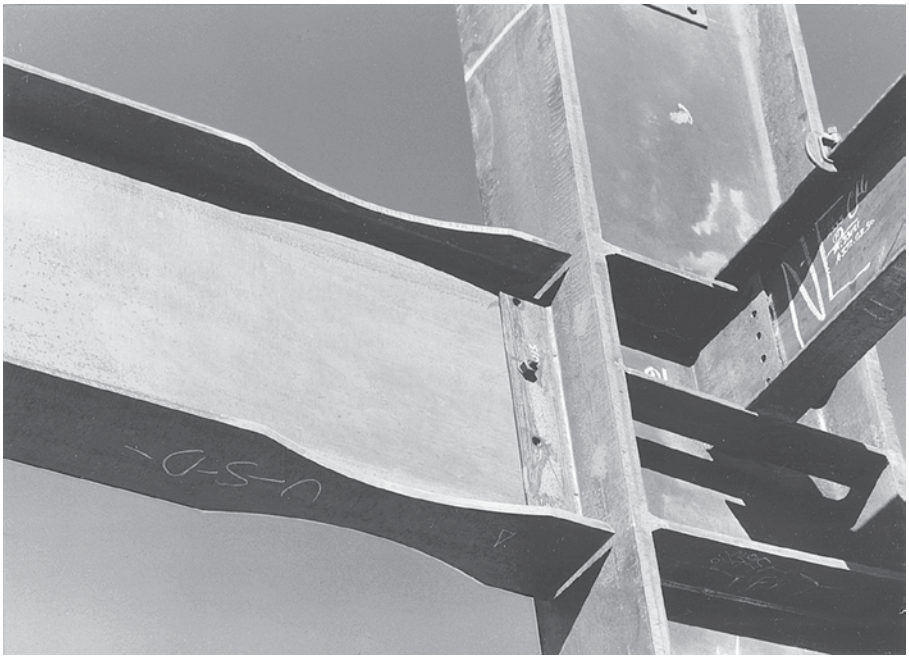


FIGURE 11.28
Photograph of a moment connection, in progress, similar to the one shown in Figure 11.27. The beam has just been bolted to a *shear tab* that is welded to the column. Next, backup bars will be welded to the column just under the beam flanges, after which the flanges will be welded to the column. *(Permission of the American Institute of Steel Construction.)*

Lateral Stability of the Building Frame

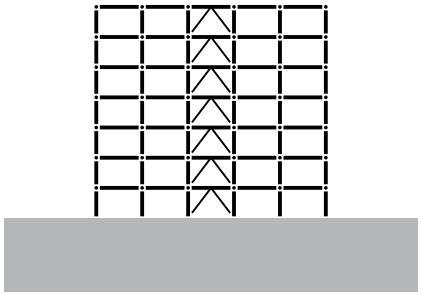
To understand the roles of shear and moment connections in the building structure, it is necessary to understand the means by which buildings are made stable against the lateral forces of wind and earthquake. Three basic *lateral force resisting systems* (LFRSs) are used, either alone or in combination: braced frames, shear walls, and moment-resisting frames (Figure 11.29). A *braced frame* uses *diagonal bracing* to create stable triangular configurations within the framework of the structure. With this system, stability is afforded by the bracing, and connections between beams and columns need not resist rotational forces. Rather, connections behave like hinges, which is another way of saying that they can be shear connections such as the one in Figure 11.26, rather than moment connections. (Though it may not be readily apparent, this type of connection is capable of the small rotations necessary for it to behave essentially as if it were free to rotate.)

A special case of the braced frame is the *eccentrically braced frame*, in which the ends of diagonal braces are offset some distance from each other where they connect to horizontal members (Figure 11.29). These connections introduce greater ductility into the building frame, important for resistance to severe earthquake forces. Like conventional braced frames, eccentrically braced frames utilize shear connections between beams and columns.

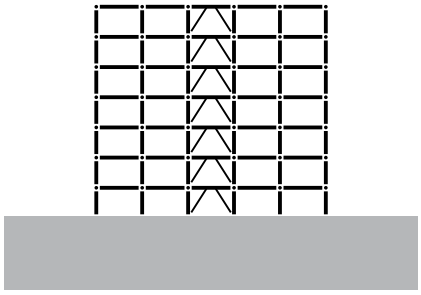
Shear walls are stiff, solid walls made of reinforced concrete, steel, or less frequently, reinforced concrete masonry. Like braced frames, they permit the use of shear connections between beams and columns elsewhere in the structural frame.

Moment-resisting frames rely on stiffer moment connections between beams and columns to impart lateral stiffness to the building frame as a whole. Depending on the configuration of the structure and the magnitude of the forces involved, not all of the connections in the frame may necessarily be moment connections. Because these connections are more difficult and expensive to make, they are used only to the extent required, with the remainder of the frame relying on less costly shear connections. In other cases, moment-resisting frames are combined with braced frames or shear walls to enhance the performance of those systems.

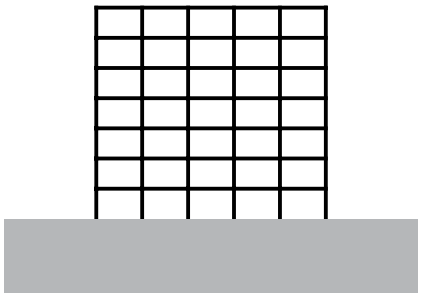
In any building, the lateral force resisting elements must be arranged in a manner that is structurally efficient as well as conducive to good architectural planning. Many arrangements and combinations are possible. In tall buildings, a common solution is a stiffened *core structure* (Figure 11.30, *top*). In this arrangement, a building's interior core or cores, the central areas containing elevators, stairs, vertical mechanical chases, and



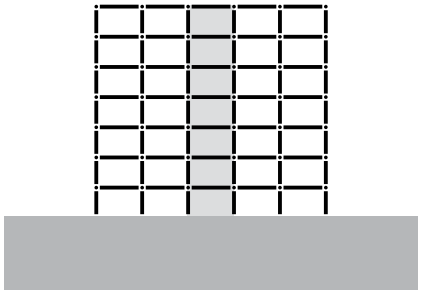
Braced Frame



Eccentrically Braced Frame



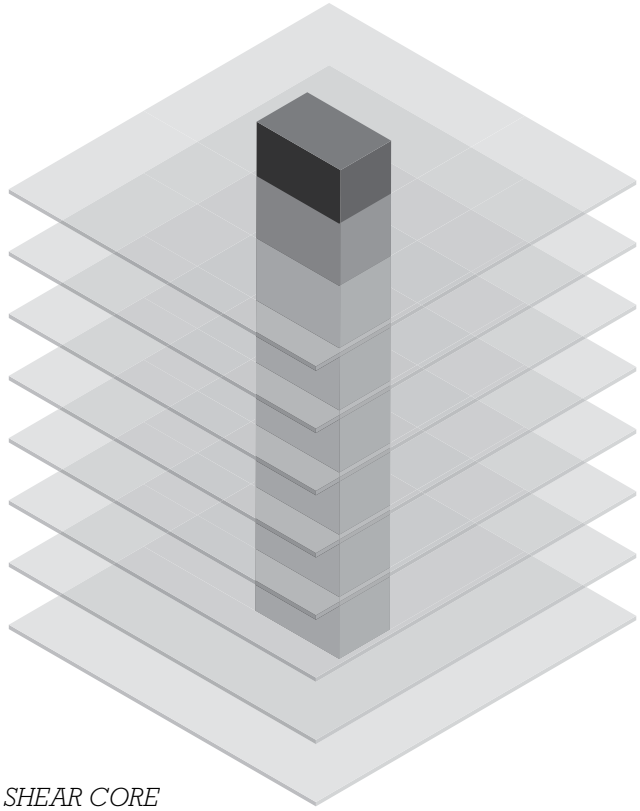
Moment-Resisting Frame



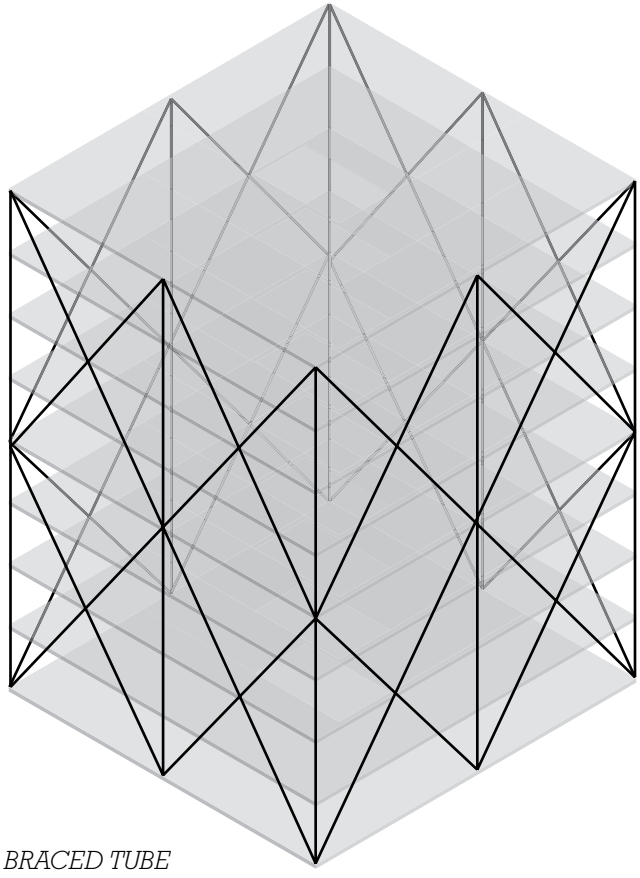
Shear Walls

FIGURE 11.29

Elevation views of the basic means for imparting lateral stability to a structural frame. Connections represented with dots are shear connections, and solid intersections indicate moment connections. The braced frame (*top*) is illustrated here with *Chevron* (or *inverted V*) *bracing*. *Crossbracing*, in which paired diagonals run from opposite corners of the braced bay, are also common. Eccentric bracing (*second from top*) is one way to increase a building frame's capacity to absorb seismic energy. The connections in the moment-resisting frame (*third from top*) are sufficiently resistant to rotation to stabilize the structure against lateral forces without bracing or shear walls. Like braced frames, shear walls (*bottom*) do not require moment connections in the structural frame.



SHEAR CORE



BRACED TUBE

FIGURE 11.30

Core structures (*top*) concentrate the lateral force resisting system at the center of the structure, leaving the remainder of the structure unencumbered by lateral force resisting elements. They may be made of shear walls, as illustrated here, or braced frames (not shown). Tube structures (*bottom*) move the lateral force resisting system to the exterior perimeter of the structure. They are made of braced frames, or less frequently, moment-resisting frames (not shown). In both diagrams shown here, only the lateral force resisting systems are shown. Other parts of the structure, such as columns resisting gravity loads only or nonstructural cores, have been omitted.

Seismic Force Resisting Systems

When considering, specifically, seismic forces acting on a building, framing systems may be classified as either special, intermediate, or ordinary. *Special seismic force resisting systems* include specially designed, highly ductile connections or framing members that can maintain the greatest levels of resilience and reliability while experiencing high stresses during extreme seismic events. *Intermediate* and *ordinary seismic force–resisting systems* are designed with progressively less extra ductility and are intended for buildings that will experience less forceful conditions. The choice between systems is based on the seismic category of the building site, building height, and cost and technical tradeoffs between possible design approaches.

The dog-bone profile of the connection in Figure 11.27, the off-axis bracing in the eccentrically braced frame in Figure 11.29, and the buckling-restrained braces in Figure 11.74 are examples of methods of introducing extra ductility into steel frames. Under extreme loadings, each of these systems provides localized areas that will experience deformations outside the normal elastic range of the material while absorbing dynamic energy imparted into the frames by the seismic shaking. Such points of controlled deformation in the frame are also sometimes called *seismic fuses*, reflecting their role as weak links, allowing localized overstressing while protecting the greater frame as a whole.

washrooms, are structured as stiff towers, using either braced framing (*braced core*) or shear walls (*shear core*). The remainder of the building frame may then be structured to resist gravity loads only, relying on the cores for lateral stability. Figure 1.11 illustrates an example of a tall building structure stabilized by a pair of reinforced concrete shear cores.

As building height increases, it becomes structurally advantageous to move some or all of the parts of lateral force resisting system to the edges of the structural frame. By distributing these elements over a greater area, the system as a whole becomes more efficient. The *tube structure* (Figure 11.30, *bottom*, and Figure 11.89) is one example, in which the lateral force resisting system forms a continuous perimeter around the frame.

Shear and Moment Connections

The American Institute of Steel Construction (AISC) defines three types of beam-to-column connections, classified according to their rotational stiffness or moment-resisting capability. *Fully restrained* (*FR*) *moment connections* are sufficiently rigid that the geometric angles between members will remain virtually unchanged under expected loadings. *Partially restrained* (*PR*) *moment connections* are not as rigid as fully restrained connections, but nonetheless possess a dependable and predictable moment-resisting capacity that can be used to stabilize a building frame. FR and PR moment connections are also sometimes referred to as rigid and semirigid connections, respectively. Both connection types can be used to construct moment-resisting building frames. *Simple connections*, otherwise known as shear connections, are considered to be capable of unrestrained rotation and to have negligible moment-resisting capacity. Buildings framed solely with simple connections must depend on diagonal bracing or shear walls for lateral stability.

Additional examples of beam-to-column connections are illustrated in Figures 11.31 through 11.36. AISC FR, PR, and simple connections are included, as well as various combinations of bolting and welding of components. Examples of column splice connections are illustrated in Figures 11.37 through 11.40.

In practice, there are a number of different ways of making any of these connections, using various connecting elements and different combinations of bolting and welding. The object is to satisfy structural requirements with the greatest possible ease and economy of construction. For standard joining conditions, the choice of which connection to use may be left to the fabricator, who has firsthand knowledge of the safest, most erectable methods that will utilize the company's labor and equipment most efficiently. For complex structures or unique joining conditions, the structural engineer may dictate a specific connection detail.

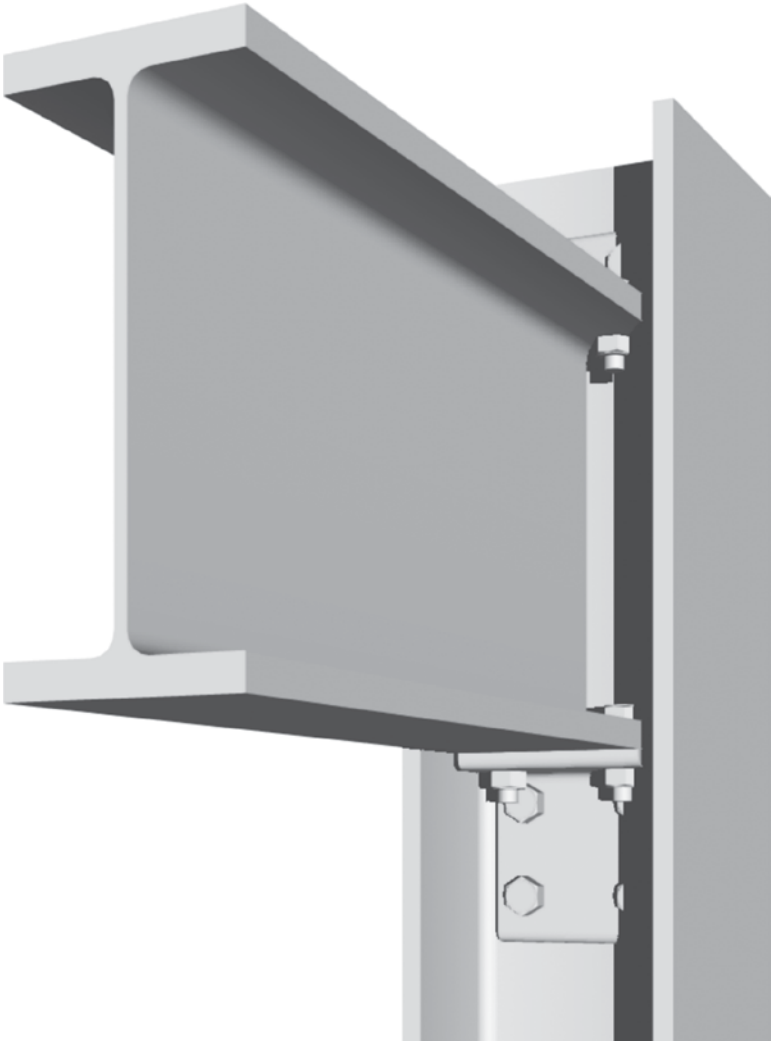


FIGURE 11.31
A *seated* beam-to-column-web connection, location *B* on the frame in Figure 11.23. Although the beam flanges are connected to the column by a seat angle below and a stabilizing angle above, this is a shear (AISC simple) connection, not a moment connection, because the two bolts are incapable of developing the full strength of the beam flange. This seated connection is used rather than a framed connection, as illustrated in Figure 11.26, to connect to a column web because there is usually insufficient space between the column flanges to insert a power wrench to tighten all the bolts in a framed connection.

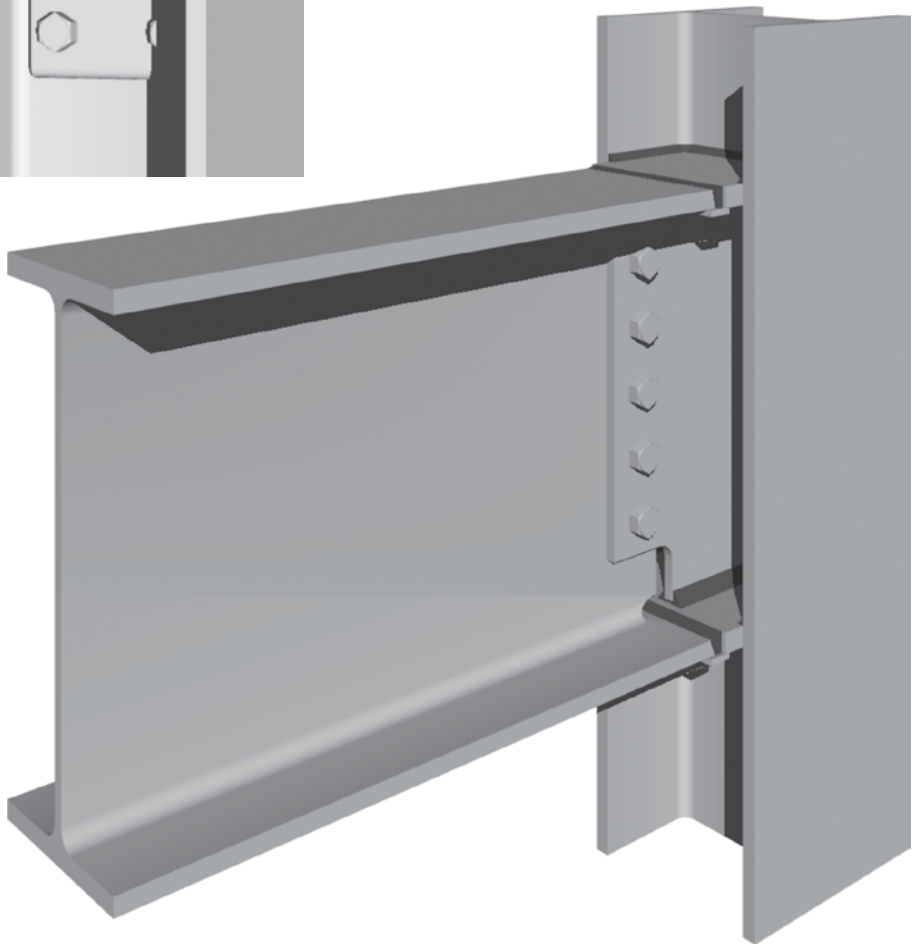


FIGURE 11.32
A welded beam-to-column-web moment (AISC fully restrained) connection, used at location *B* on Figure 11.23 when a rigid connection is required. A vertical shear tab, welded to the web of the column at its centerline, serves to receive bolts that join the column to the beam web and hold the beam in place during welding. The horizontal stiffener plates that are welded inside the column flanges are thicker than the beam flanges and extend out beyond the column flanges to reduce concentrations of stress at the welds.

FIGURE 11.33
A single-tab shear (AISC simple frame) connection is an economical alternative to the connection shown in Figure 11.26 when the load on the connection is relatively light. A single connector plate is welded to the column in the shop, and the beam is bolted to it on the construction site.

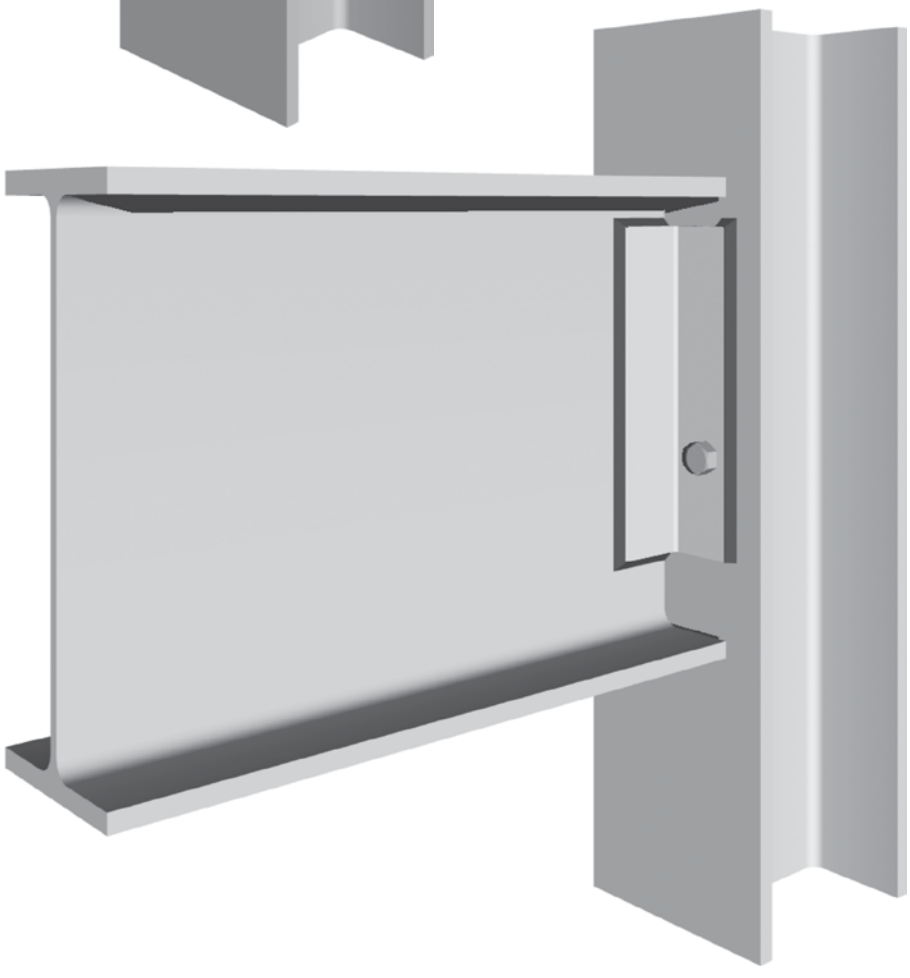


FIGURE 11.34
Shear (AISC simple frame) connections may also be made entirely by welding. The angles are welded to the beam in the shop. Bolts through the angles hold the beam in place while it is welded to the column. The angles are not welded to the column along their top and bottom edges. This permits the angles to flex slightly to allow the beam to rotate away from the column as it bends.

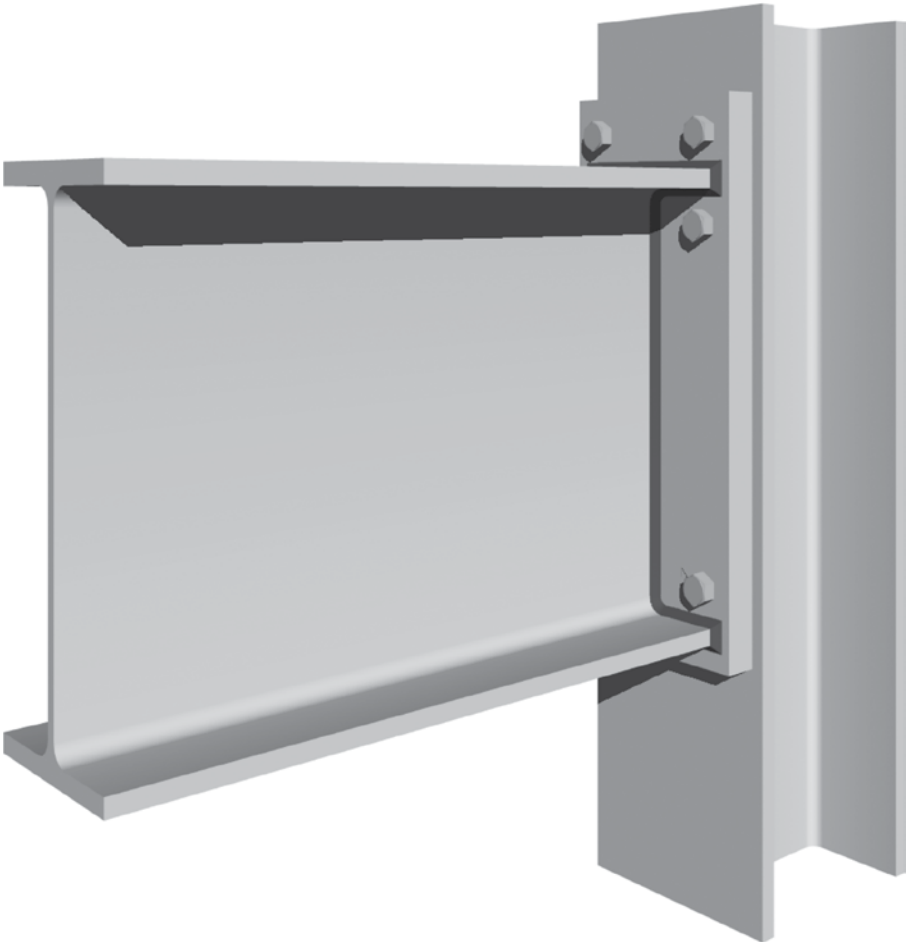


Figure 11.35
A welded/bolted *end plate* beam–column connection. As shown, this is a semirigid (AISC partially restrained) connection. With more bolts, this can become a rigid, AISC fully restrained connection, which could be used to support a short cantilever beam such as the one at location *C* in Figure 11.23. The plate is welded to the end of the beam in the shop and bolted to the column on the building site.

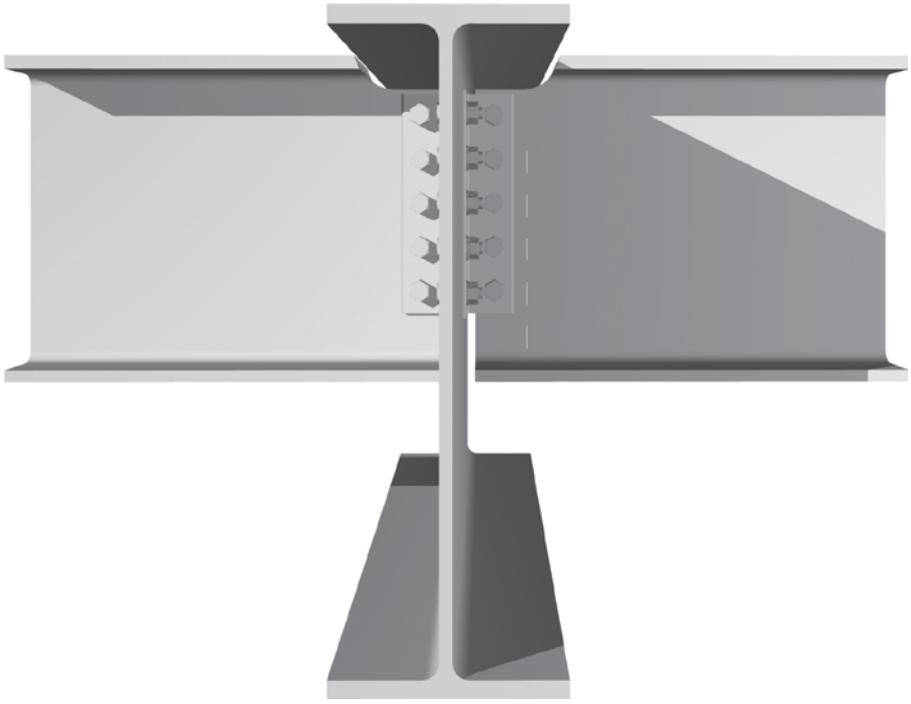


Figure 11.36
A coped beam–girder shear (AISC simple) connection, used at location *D* in Figure 11.23. A girder is a beam that supports other beams. This connection may also be made with single tabs rather than angles if the load is not too great. The top flanges of the beams are cut away (coped) so that the tops of the beams and the girder are all level with one another, ready to receive the floor or roof decking. Bending moments at the ends of a beam are normally so small that the flanges may be coped without compromising the strength of the beam.

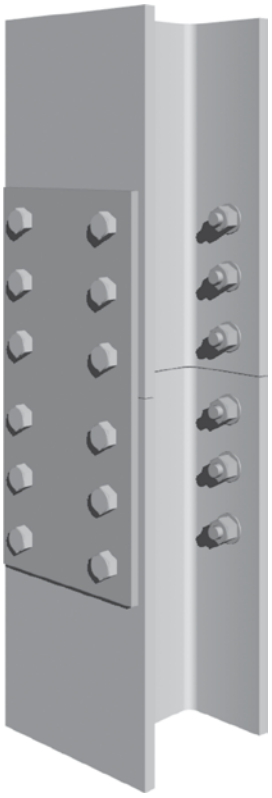


Figure 11.37
A bolted column–column connection for columns that are the same size. The plates are bolted to the lower section of the column in the shop and to the upper section on the site. All column connections are made at waist height above the floor, location *E* in Figure 11.23.

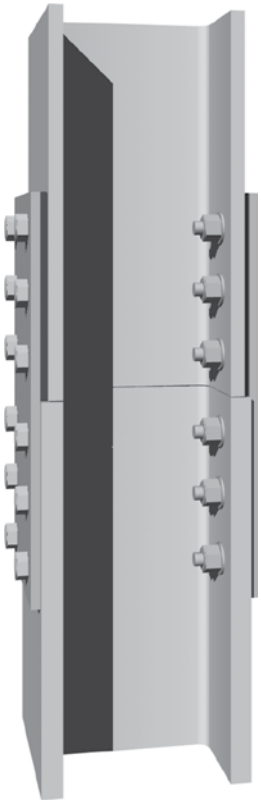


Figure 11.38
Column sizes diminish as the building rises, requiring frequent use of shim plates at connections to make up for differences in flange thicknesses.

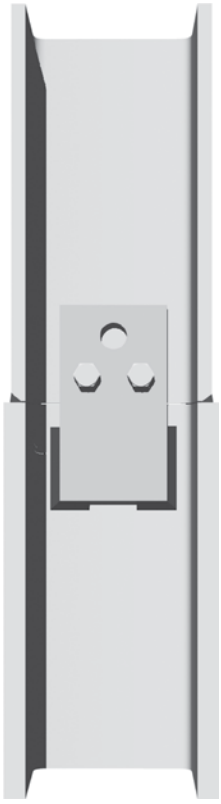


Figure 11.39
Column connections may be welded rather than bolted. The connector plate is welded to the lower column section in the fabricator's shop. The hole in the connector plate is used to attach a lifting line during erection. The bolts hold the column sections in alignment, while the flanges are connected in the field with partial-penetration welds in bevel grooves. Partial-penetration welding allows one column to rest on the other prior to welding.

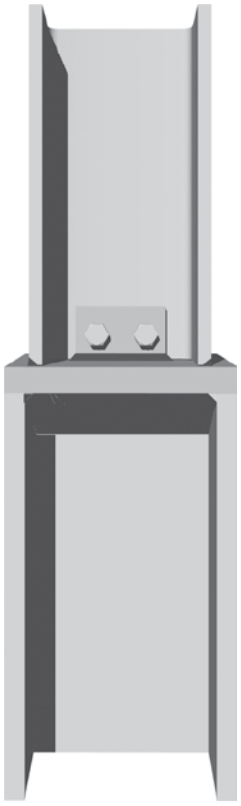


Figure 11.40
A welded butt plate connection is used where a column changes from one nominal size of wide flange to another. The thick butt plate, which is welded to the lower column section in the shop, transfers the load from one section of column to the other. The partial-penetration weld at the base of the upper column is made at the site.

The Construction Process

A steel building frame begins as a rough sketch on the drafting board of an architect or engineer (Figure 11.41). As the building design process progresses, the sketch evolves through many stages of drawings and calculations to become a finished set of structural drawings. These show accurate column locations, the shapes and sizes of all the members of the frame, and all the loads of the members, but they do not give the exact length to which each member must be cut to mate with the members it joins, and they do not give details of the more routine connections of the frame. These are left to be worked out by a subsequent recipient of the drawings, the *fabricator*.

The Fabricator

The fabricator's job is to deliver to the construction site steel components that are ready to be assembled without further processing. This work begins with the preparation in the fabricator's shop of detailed *shop drawings* that show exactly how each piece will be made and what its precise dimensions will be. The fabricator designs connections to transmit the loads indicated by the engineer's drawings. Within the limits of accepted engineering practice, the fabricator is free to design the connections to be made as economically as possible, using various combinations of welding and bolting that best suit available equipment and expertise. The fabricator also prepares drawings to show the general contractor exactly where and how to install foundation anchor bolts to connect to the columns of the building and to guide the erector in assembling the steel frame on the building site. When completed, these shop drawings are submitted to the engineer and the architect for review and approval to be sure that they conform exactly to the intentions of the design team. Meanwhile, the fabricator places an order with a producer of steel for the stock from which the structural steel members will be fabricated. (The major beams, girders, and columns are usually ordered cut to exact length by the mill.) When the approved shop drawings, with corrections and comments, are returned to the fabricator by the design team, revisions are made as necessary, and full-size templates of cardboard or wood are prepared as required to assist the shop workers in laying out the various connections on the actual pieces of steel.

Plates, angles, and tees for connections are brought into the shop and cut to size and shape with gas-fueled cutting torches, power shears, and saws. With the aid of the templates, bolt hole locations are marked. If the plates and angles are not unusually thick, the holes may be made rapidly and economically with a punching machine. In very thick stock, or in pieces that will not fit conveniently into the punching machines, holes are drilled rather than punched.

Pieces of steel stock for the beams, girders, and columns are brought into the fabricator's shop with an overhead traveling crane or conveyor

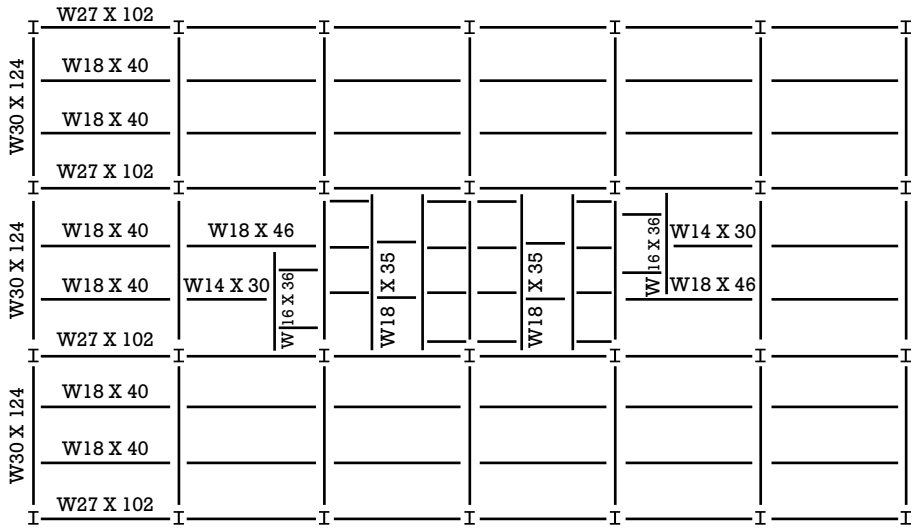


Figure 11.41
A typical framing plan for a multistory steel-framed building, showing size designations for beams and girders. Notice how this frame requires beam-to-column-flange connections where the W30 girders meet the columns, beam-to-column-web connections where the W27 beams meet the columns, and coped beam–girder connections where the W18 beams meet the W30 girders. The small squares in the middle of the building are openings for elevators, stairways, and mechanical shafts. An architect's or engineer's framing plan would also give dimensions between centers of columns and would indicate the magnitudes of the loads that each joint must transfer, to enable the fabricator to design each connection.

system. Each piece is stenciled or painted with a code that tells which building it is intended for and exactly where it will go in the building. With the aid of the shop drawings, each piece is measured and marked for its exact length and for the locations of all holes, stiffeners, connectors, and other details. Cutting to length, for those members not already cut to length at the mill, is done with a power saw or a flame-cutting torch. The ends of column sections that must bear fully on the baseplates or on one another are squared and are made perfectly flat by sawing, milling, or facing. In cases where the columns will be welded to one another, and for beams and girders that are to be welded, the ends of the flanges are beveled as necessary. Beam flanges are *coped* as required. Bolt holes are punched or drilled (Figure 11.42). *Plasma* (high-temperature ionized gas) *cutting* and *laser cutting* are also used in steel fabrication. Both of these types of devices can be driven by machines that allow the fully automated cutting and shaping of parts from digitally prepared models.

Where called for, beams and girders are *cambered* (curved slightly in an upward direction) so that they will deflect into a straight line under load. Cambering may be accomplished by a hydraulic ram that bends the beam enough to force a permanent deformation. Steel shapes can also be bent to a smooth radius with a large machine that passes the shape through three rollers that flex it sufficiently to impart a permanent curvature, or they can be fabricated into more complex geometries (Figure 11.43). An older, much more costly means of cambering involves heating local areas of one flange of the member with a large oxyacetylene torch. As each area is heated to a cherry-red color, the metal softens, expands, and deforms to make a slight bulge in the width and thickness of the flange because the surrounding steel, which is cool, prevents the heated flange from

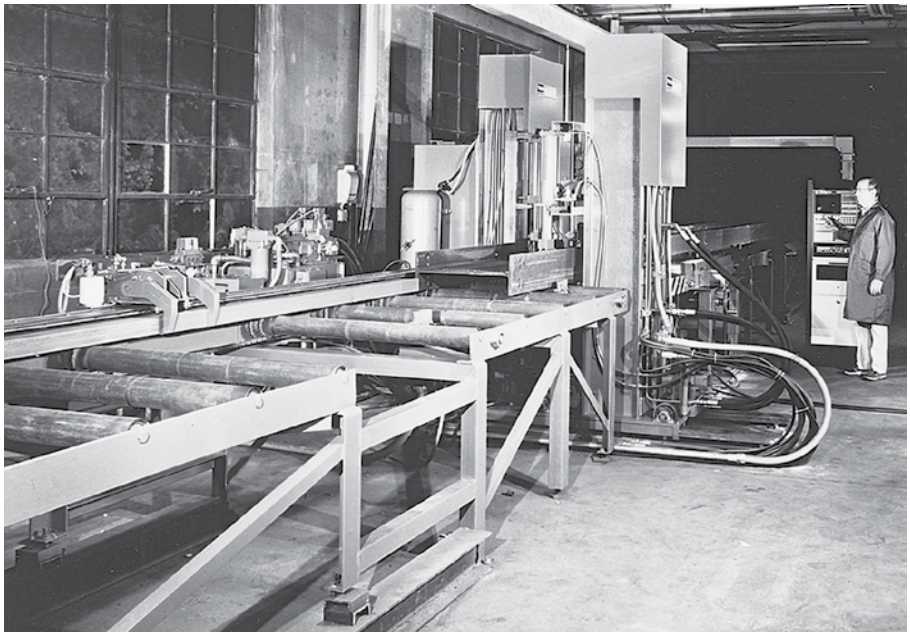


FIGURE 11.42
Punching bolt holes in a wide-flange beam. *(Courtesy of W.A. Whitney Corp., an Esterline Company.)*

FIGURE 11.43
Structural steel members, formed into complex shapes in the fabricator's shop, are welded together on site to create the structural framework for the Amazon Spheres, designed by NBBJ. *(Photo by Joseph Iano.)*

lengthening. As the heated flange cools, the metal contracts, pulling the member into a slight bend at that point. By repeating this process at several points along the beam, a camber of the desired shape and magnitude is produced.

As a last step in fabricating beams, girders, and columns, stiffener plates are welded to each piece as required, and connecting plates, angles, and tees are welded or bolted at the appropriate locations (Figure 11.44). As much connecting as possible is done in the shop, where tools are handy and access is easy. This saves time and money during erection, when tools and working conditions are less optimal and total costs per worker-hour are higher.

Plate girders, built-up columns, trusses, and other large components are assembled in the shop in units as large as can practically be transported to the construction site, whether by truck, railway, or barge. Intricate assemblies such as large trusses are usually preassembled in their entirety in the shop, to be sure that they will go together smoothly in the field, then broken down again into transportable components.

As the members are completed, each is straightened, cleaned, and prime painted as necessary, and inspected for quality and for conformance to the job specifications and shop drawings. The members are then taken from the shop to the fabricator's yard by crane, conveyor, trolley, or forklift, where they are organized in stacks according to the order in which they will be needed on the building site.

As an alternative to the traditional shop drawing process just described, a structural engineer may use three-dimensional modeling software to design the steel connections and supply digital data to the fabricator to automatically guide the fabricator's equipment. While this method requires the engineer to assume more responsibility for the final design of the steel connection details, it also can shorten the time required for steel to arrive on site and can improve the coordination between the structural steel and other building systems.

The Erector

Where the fabricator's job ends, the *erector's* job begins. Some companies both fabricate and erect, but more often the two operations are done by separate entities. The erector is responsible for assembling into a

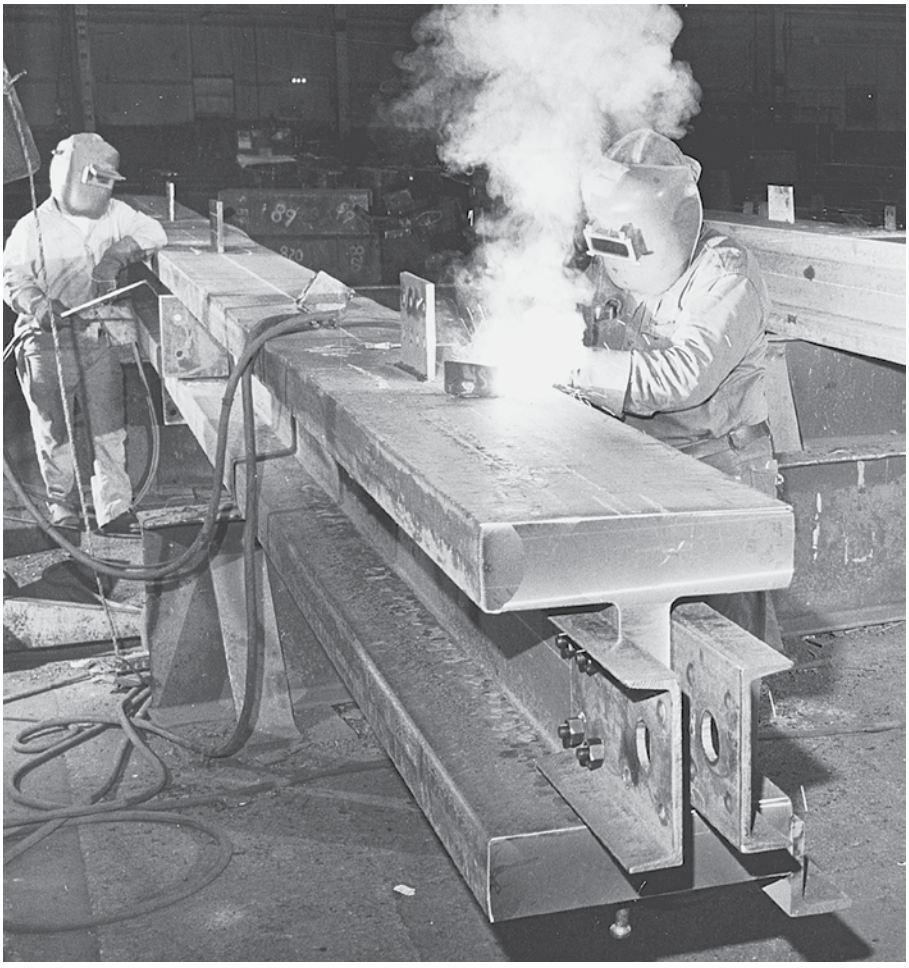


FIGURE 11.44
Welders attach connector plates to an exceptionally heavy column section in a fabricator's shop. The twin channels bolted to the end of the column will be used to attach a lifting line for erection, after which they will be removed and reused. *(Courtesy of U.S. Steel Corp.)*

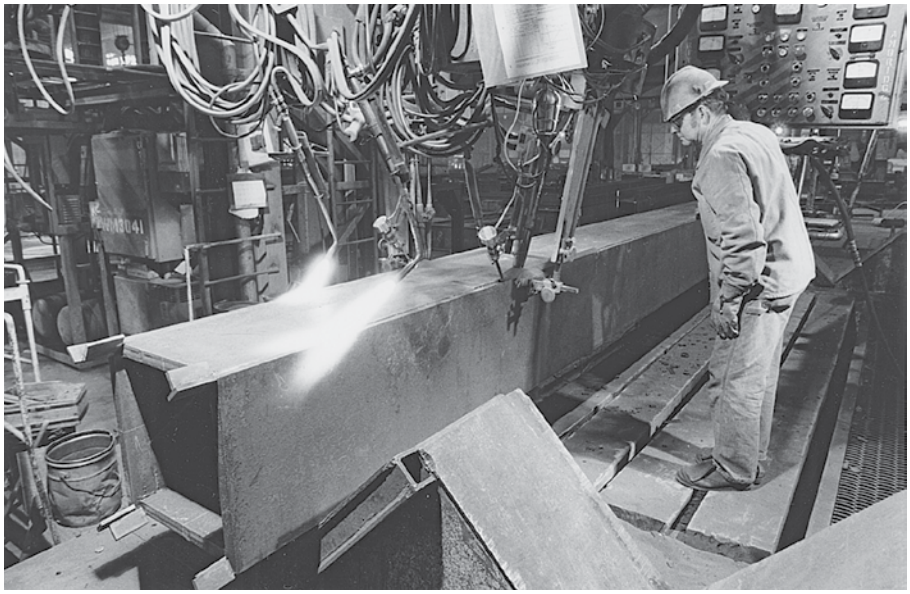


FIGURE 11.45
Machine welding plates together to form a box column. The torches to the left preheat the metal to help avoid thermal distortions in the column. Mounds of powdered flux around the electrodes in the center indicate that this is the submerged arc process of welding. The small steel plates tacked onto the corners of the column at the extreme left are runoff bars, which are used to allow the welding machine to go past the end of the column to make a complete weld. These will be cut off as soon as welding is complete. *(Courtesy of U.S. Steel Corp.)*

frame on the building site the steel components furnished by the fabricator. The erector's workers, by tradition, are called *ironworkers*.

Erecting the First Tier

Erection of a multistory steel building frame starts with assembly of the first *tier* of framing. Lifting of the steel components may begin with either some type of mobile crane or (on larger projects) fixed tower cranes (Figure 11.48). In accordance with the erection drawings prepared by the fabricator, the columns, usually furnished in sections two stories tall, are picked up from organized piles on the site or directly from the trucks they are delivered on and lowered carefully over the anchor bolts and onto the foundation, where the ironworkers bolt them down.

There are 175,000 ironworkers in this country . . . and apart from our silhouettes ant-size atop a new bridge or skyscraper, we are pretty much invisible.

—Mike Cherry, *On High Steel: The Education of an Ironworker*, 1974, p. xiii

Foundation details for steel columns vary (Figure 11.46). Steel *baseplates*, which distribute the concentrated loads of the steel columns across a larger area of the concrete foundation, are shop-welded to all but the largest columns. The foundations and anchor bolts were put in place previously by the general contractor, following the plan prepared by the fabricator. The contractor may, if requested, provide thin steel *leveling plates* that are set perfectly level at the proper height on a bed of *grout* atop each concrete foundation. The baseplate of the column rests upon the leveling plate and is held down with the protruding anchor bolts. Alternatively, especially for larger baseplates with four anchor bolts, the leveling plate is omitted. The column is supported at the proper elevation on stacks of steel shims inserted between the baseplate and the foundation, or on leveling nuts placed beneath the baseplate on the anchor bolts. After the first tier of framing is plumbed up (as described later in this section), the baseplates are grouted and the anchor bolts tightened. For very large, heavy columns, baseplates are shipped independently of the columns (Figure 11.47). Each is leveled in place with shims, wedges, or shop-attached leveling screws, then grouted prior to column placement.

After the first tier of two-story-tall columns has been erected, the beams and girders for the first two stories are bolted in place. First, a *raising gang*, working with a crane, positions the components and inserts enough bolts to hold them together temporarily. A gang of bolters follows behind, inserting bolts in all the holes and partially tightening them. The two-story tier of framing is then *plumbed up* (straightened and squared) with diagonal cables and turnbuckles while checking the alignment with plumb bobs, transits, or laser levels. When the tier is plumb, connections are tightened, baseplates are grouted if necessary, welds are made, and permanent diagonal braces, if called for, are attached. Ironworkers scramble back and forth, up and down on the columns and beams, protected from falling by safety harnesses that are connected to steel cable lifelines.

At the top of the tier, a level platform is created to facilitate work on the next tier of framing to follow. Most commonly, this consists of corrugated steel decking installed on top of the upper level beam and girder framing that will become part of the permanent floor structure.

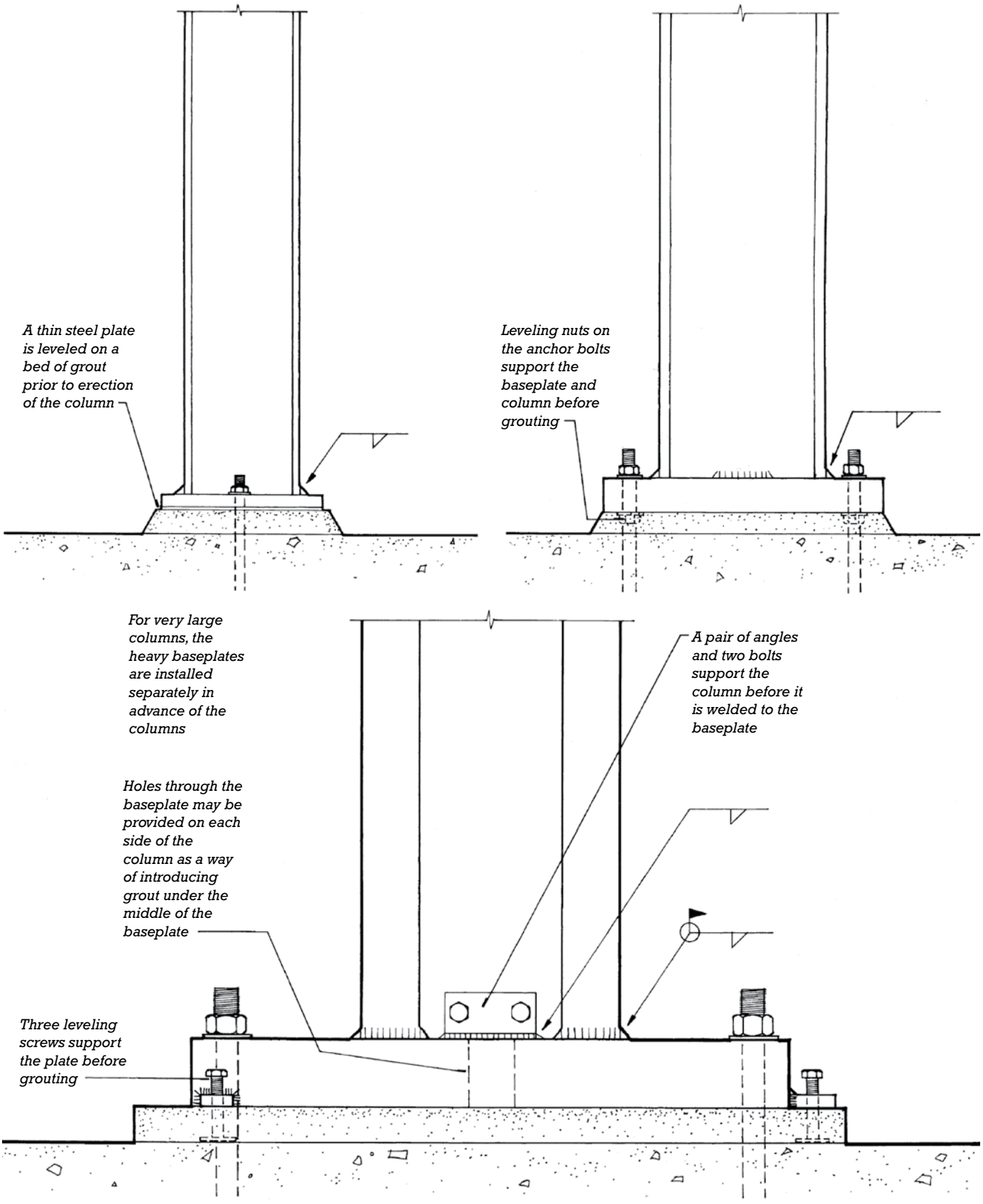

A thin steel plate is leveled on a bed of grout prior to erection of the column
Leveling nuts on the anchor bolts support the baseplate and column before grouting
For very large columns, the heavy baseplates are installed separately in advance of the columns
A pair of angles and two bolts support the column before it is welded to the baseplate
Holes through the baseplate may be provided on each side of the column as a way of introducing grout under the middle of the baseplate
Three leveling screws support the plate before grouting

FIGURE 11.46
Three typical column base details. ***Upper left*: A small column with a welded baseplate set on a steel leveling plate.** ***Upper right*: A larger column with a welded baseplate set on leveling nuts.** ***Below*: A heavy column field-welded to a loose baseplate that has been previously leveled and grouted.**

Or, where installation of the permanent floor decking is not practical at this time, temporary decking may be used or safety netting is installed to protect workers above from falls and workers below from falling objects. The tier columns extend roughly to waist level above the working platform, so as to avoid conflict between the beam–column connections and the column splices to come, and to position the splices at a convenient working level.

Erecting the Upper Tiers

Erection of the second tier proceeds much like that of the first. The next tier of two-story column sections are hoisted into position and connected by splice plates to the tops of the first tier of columns extending above the working platform. The beams and columns for the two floors are set, the tier is plumbed and tightened up, and another layer of permanent or temporary decking, or safety netting, is installed (Figures 11.49 through 11.56).

FIGURE 11.47
Ironworkers guide the placement of a very heavy column fabricated by welding together two rolled wide-flange sections and two thick steel plates. It will be bolted to its baseplate through the holes in the small plate welded between the flanges on either side. *(Courtesy of Bethlehem Steel Corporation.)*

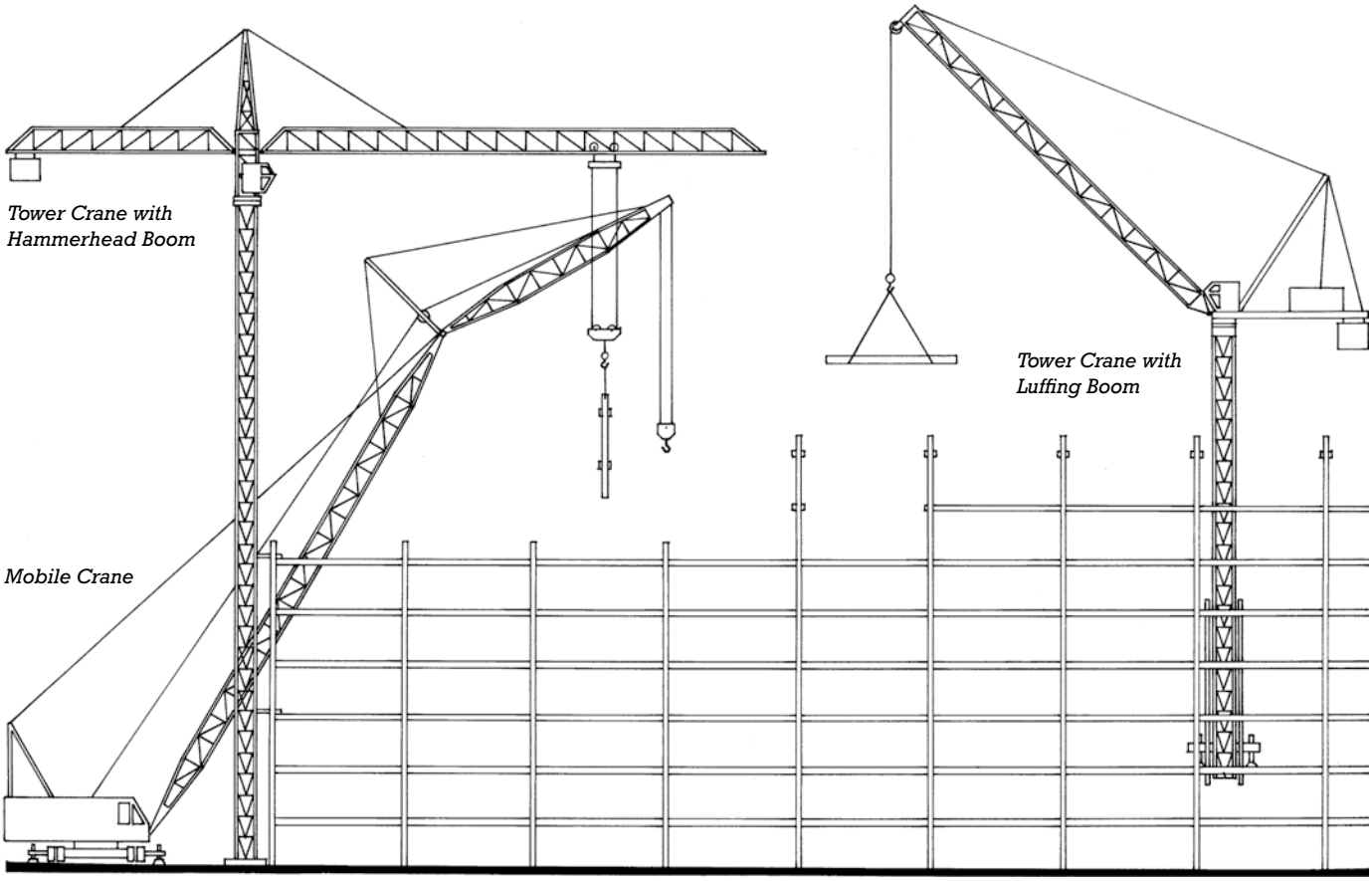


FIGURE 11.48
Two common types of *tower cranes* and a mobile crane. The *luffing-boom crane* is useful in congested situations where the wide arc of the *hammerhead boom crane* could be limited by obstructions. Tower cranes can either be supported on their own foundations, or, in the case of internal cranes, they may also be supported by the frame of the building. With very tall buildings, tower cranes climb as the building rises by means of self-contained hydraulic jacks.

FIGURE 11.49
An ironworker clips his body harness to a safety line as he moves around a column. *(Photo by James Digby, courtesy of L.P.R. Construction Company.)*

FIGURE 11.50
A tower crane lowers a series of beams to ironworkers. The worker to the left uses a tagline to maneuver the beam into the proper orientation. *(Photo by James Digby, courtesy of L.P.R. Construction Company.)*

If the building is not too tall, a mobile crane will do the lifting for the entire building. For a taller building, tower cranes are used (Figure 11.48). The tower crane builds itself an independent tower as the building rises, either alongside the building or within an elevator shaft or a vertical space temporarily left open in the frame.

As each piece of steel is lowered toward its final position in the frame, it is guided by an ironworker who holds a rope called a *tagline*, the other end of which is attached to the piece. Other ironworkers in the raising gang guide the piece by hand as soon as they can reach it, until its bolt holes align with those in the mating pieces (Figures 11.51 and 11.52). Sometimes crowbars or hammers must be used to pry, wedge, or drive components until they fit properly, and bolt holes may, on occasion, have to be reamed larger to admit bolts through slightly misaligned pieces. When an approximate alignment has been achieved, tapered steel *drift pins* from the ironworker's tool belt are shoved into enough bolt holes to hold the pieces together until a few bolts can be inserted. The bolters follow behind the raising gang, filling the remaining holes with bolts from leather carrying baskets and tightening them first with hand wrenches and then with impact wrenches. Field-welded connections are initially held in alignment with bolts, then welded when the frame is plumb.

The last beam is placed at the top of the building with a degree of ceremony appropriate to the magnitude of the building. At the very least, a small evergreen tree, a national flag, or both are attached to the beam before it is lifted (Figures 11.55 and 11.56). For major buildings, assorted dignitaries are likely to be invited to a building-site *topping-out* party.

FIGURE 11.51
Connecting a beam to a column. *(Courtesy of Bethlehem Steel Corporation.)*

FIGURE 11.52
Ironworkers attach a girder to a box column. Each worker carries two combination wrench–drift pin tools in a holster on his belt and inserts the tapered drift pins into each connection to hold it until a few bolts can be added. Bundles of corrugated steel decking are ready to be opened and distributed over the beams to make a floor deck. *(Courtesy of Bethlehem Steel Corporation.)*

FIGURE 11.53
Bolting heavy joist girders to a column. *(Courtesy of Vulcraft Division of Nucor.)*

FIGURE 11.54
Welding open-web steel joists to a wide-flange beam. *(Courtesy of Vulcraft Division of Nucor.)*

FIGURE 11.55
Topping out: The last beam in a steel frame is special. *(Courtesy of U.S. Steel Corp.)*

FIGURE 11.56
A 10-story steel frame nears completion. The lower floors have already been decked with corrugated steel decking. *(Courtesy of Vulcraft Division of Nucor.)*

If nobody plumbed-up, all the tall buildings in our cities would lean crazily into each other, their elevators would scrape and bang against the shaft walls, and the glaziers would have to redress all the windowglass into parallelograms. . . . What leaned an inch west on the thirty-second floor is sucked back east on the thirty-fourth, and a column that refused to quit leaning south on forty-six can generally be brought over on forty-eight, and by the time the whole job is up the top is directly over the bottom.

—Mike Cherry, *On High Steel: The Education of an Ironworker*, 1974, pp. 110–111

Floor and Roof Decking

In early steel frame buildings, shallow arches of brick or tile were constructed between supporting steel beams, tied with steel tension rods, and filled over with concrete to produce level floor surfaces (Figure 11.57). These were heavier than the metal deck systems commonly used today and required larger framing members to carry their weight. They were also more labor intensive.

Metal Decking

Metal decking (Figures 11.58 through 11.61) is made of thin sheets of steel that have been cold-formed into a corrugated shape to increase strength and stiffness. The spanning capability of the deck is determined mainly by the thickness of the sheet from which it is made and the depth of the corrugations.

For floors, metal decking is combined with a concrete topping to create a complete floor. *Form deck* is metal decking that acts as formwork only, supporting the wet concrete when the concrete is first poured. Though it remains permanently in place, it does not participate in the structural behavior of the floor once the concrete has hardened. *Composite metal deck* is designed so that once the concrete has hardened, the two materials behave as a unified element, or *composite floor slab*. Embossing (dimples), lugs, holes, or welded wires added to the metal panels cause the decking and hardened concrete to mechanically interlock, allowing the decking to act as tensile reinforcing for the concrete. Composite floor slabs can span further and are stiffer than noncomposite slabs of the same thickness.

Roof deck is used without concrete topping. Its corrugations are usually more closely spaced to better support the types of roof insulation boards commonly placed on top.

Cellular deck is made by welding a flat metal sheet to the underside of a corrugated sheet during deck manufacture. Cellular decking is stiffer and can span further than non-cellular decking. The hollow cells can be used to conceal electrical power and communications wiring in the floor. Or, when a perforated flat sheet is used, acoustical insulation can be inserted within the cells to create an acoustical surface that reduces the reflection of sound in the space below. Form deck, composite metal deck, and roof deck can all be made as cellular deck.

Metal decking is fastened to the supporting steel framing by welding, self-drilling screws, or power-driven pins. Welding takes longer to complete than mechanical fastening, but it is also stronger. It takes the form of regularly spaced welded spots (*arc spot welds* or *puddle welds*) or short welded seams (*arc seam welds*) that fuse the decking and supporting steel member.

Composite Beam Construction

Composite beam construction takes composite construction a step further than composite slab to include the supporting beams in the composite behavior. Before concrete is poured over the metal deck, *shear studs* are welded every few inches to the top of each beam, using a special electric welding gun (Figures 11.62 and 11.63). The purpose of the studs is to interlock the beam and concrete such that that two act in a unified fashion. When the complete floor structure is subsequently loaded, a

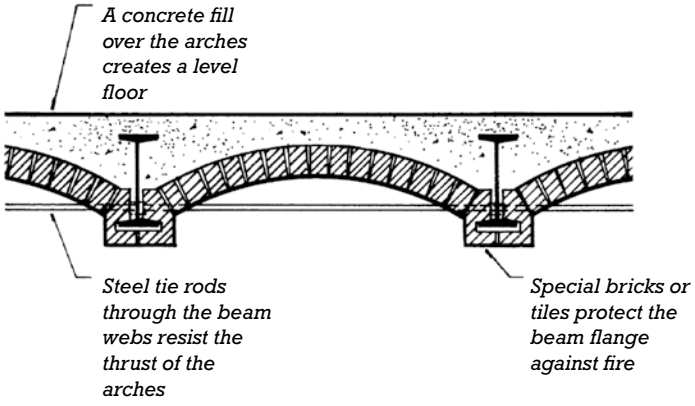


FIGURE 11.57
Tile or brick arch flooring is found in many older steel frame buildings.

Figure 11.58
There are three types of corrugated metal decking in this image. The roof decking above has smaller, more closely spaced corrugations than the composite floor decking on the level below. A single sheet of decking with even deeper, more widely spaced corrugations has been laid across the framing in the foreground, but not yet fastened in place. *(Photo by Joseph Iano.)*

Interactive Exercise

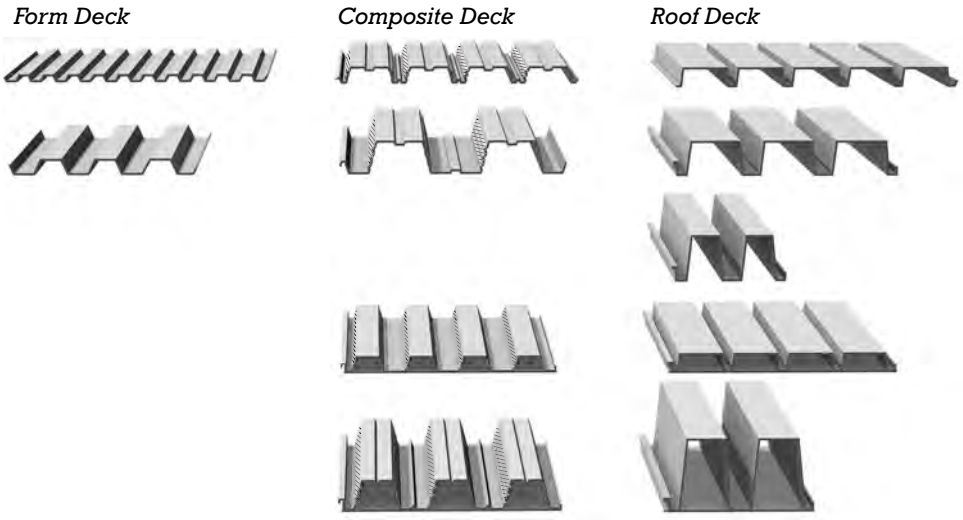


Figure 11.59
Common profiles of corrugated steel decking. Standard depths of form decking range from 1½ to 2½ inches (13 to 64 mm). Composite decking depths range from 1½ and 3 inches (38 and 76 mm). Roof decking is available in depths of 1½ to 7 inches (38 to 178 mm). The bottom two examples of composite and roof decking are cellular. Metal thicknesses range from 0.027 to 0.054 inches (0.68 to 1.37 mm).

Figure 11.60
Samples of corrugated steel decking. The second sample from the bottom achieves composite action by keying of the concrete topping to the deformations in the decking. The bottom sample has a closed end, which is used at the perimeter of the building to prevent the concrete topping from escaping during pouring. *(Courtesy of Wheeling Corrugating Company Division, Wheeling-Pittsburgh Steel Corp.)*

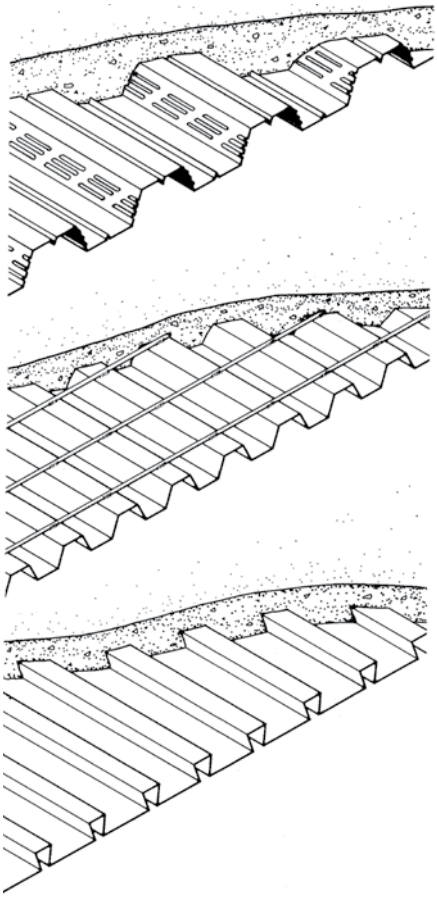


Figure 11.61
Composite decking acts as steel reinforcing for the concrete topping installed over it. The top example bonds to the concrete with deformed ribs and the middle example with welded steel rods. The bottom type makes an attractive ceiling texture if left exposed and furnishes dovetail channels for the insertion of special fastening devices to hang ductwork, piping, conduits, and machinery from the ceiling.

strip of the concrete slab acts in compression as the steel shape resists tension. This increases the loadbearing capacity of the combined slab–beam system and results in an overall lighter and less costly structure.

Concrete Decks

Concrete floor and roof slabs are also used in steel building frames instead of metal decking and concrete fill. Concrete may be poured in place over temporary wood or metal forms, or precast concrete planks may be lifted and set into place (Figure 11.64). Precast concrete decks are relatively light in weight and quick to erect, even under weather conditions that would delay the pouring of concrete. Usually, a thin, poured-in-place concrete topping is added later during construction, to produce a smooth floor.

Other Roof Decking

In noncombustible construction, the corrugated steel decking is the most prevalent roof decking material. In combustible construction, roof decks may also be constructed

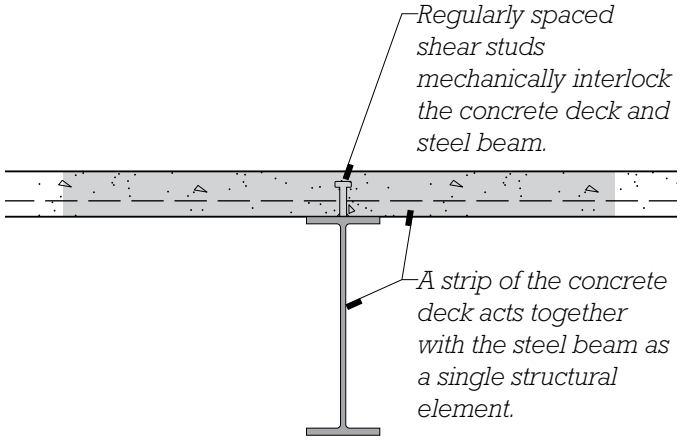


FIGURE 11.62
Composite beam construction. Shear studs are not welded to beams in the fabricator's shop because of the tripping hazard they could present during steel erection.

FIGURE 11.63
Pouring a concrete fill on a steel roof deck, using a concrete pump to deliver the concrete from the street below to the point of the pour. Shear studs are plainly visible over the lines of the beams below. The welded wire reinforcing strengthens the concrete against cracking. *(Courtesy of Schwing America, Inc.)*

of heavy timber decking, structural wood panel sheathing, panels of wood fiber bonded together with portland cement, or other lightweight board products, used alone or as formwork in combination with lightweight insulating concrete toppings.

Architectural Structural Steel

Where structural steel members will remain exposed in the finished building and a high standard of appearance quality is desired, steel may be specified as *architecturally exposed structural steel (AESS)*. AESS specifications may include special requirements for dressing and finishing of welds, closer tolerances in connections between members, removal of marks made on the steel during fabrication, application of high-quality finishes, and other considerations (Figure 11.65).

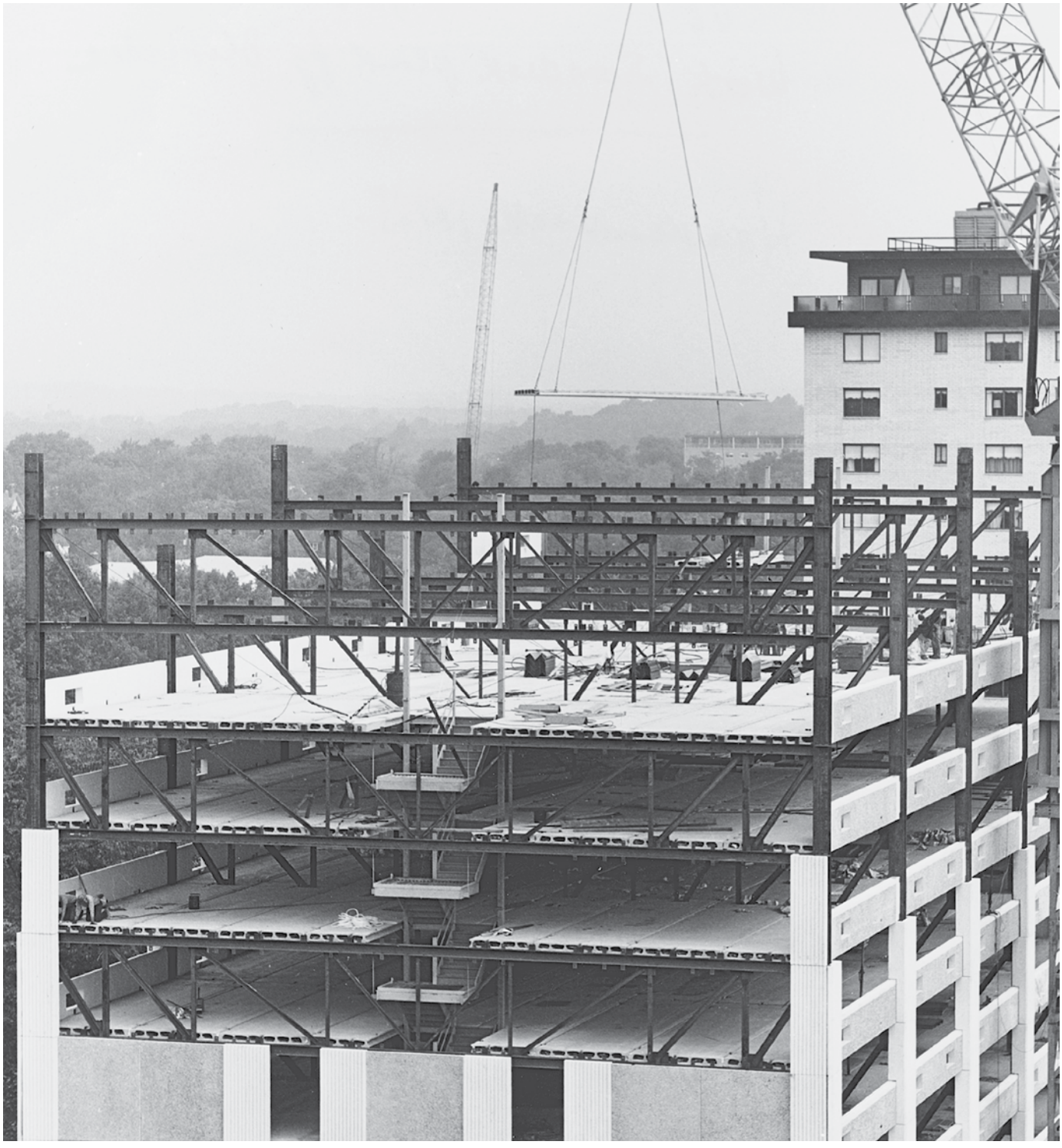


Figure 11.64
A tower crane installs precast concrete hollow-core planks for floor decks in an apartment building. Precast concrete is also used for exterior cladding of the building. The steel framing is a design known as the staggered truss system, in which floors are supported by full story-height steel trusses at alternate levels of the building. The trusses are later enclosed with interior partitions. *(Courtesy of Blakeslee Prestress, Inc.)*

FIGURE 11.65
Architectural steel tree-like columns, fabricated from HSS round members, support curved rolled structural sections in this rail transportation station. *(Photo by Joseph Iano.)*

FIRE PROTECTION OF STEEL FRAMING

Normal building fires are not hot enough to melt steel, but they can be hot enough to weaken steel sufficiently to cause the steel to lose its strength and fail (Figures 11.66 and 11.67). For this reason, building codes generally limit the use of unprotected steel framing to buildings of no more than two to five stories in height, in which escape can be made rapidly in the case of fire. For taller buildings, it is necessary to protect the steel frame from heat long enough for the building to be fully evacuated and the fire extinguished or allowed to burn out on its own.

Fireproofing (*fire protection* being a more accurate term) of steel framing was originally done by encasing steel beams and columns in brick masonry (Figure 11.57) or poured concrete. These heavy encasements were effective, absorbing heat into their great mass and dissipating some of it through dehydration of the mortar and concrete, but their weight added considerably to the load that the steel frame had to bear. This added, in turn, to the weight and cost of the

FIGURE 11.66
An exposed steel structure following a prolonged fire in the highly combustible contents of a warehouse. *(Courtesy of National Fire Protection Association, Quincy, MA.)*

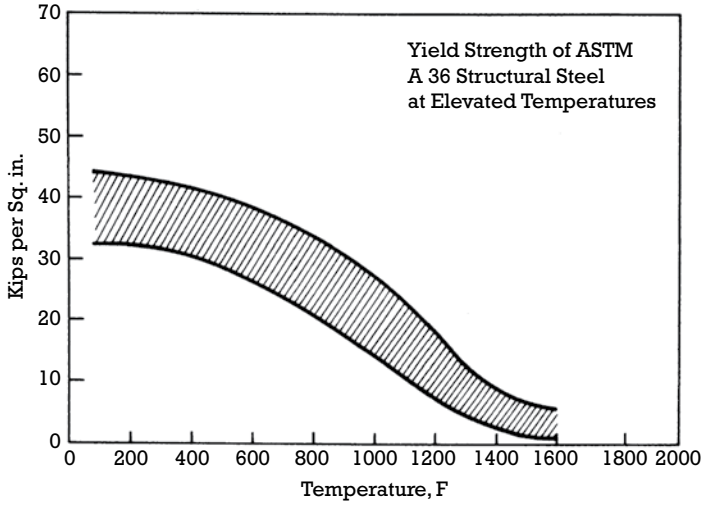
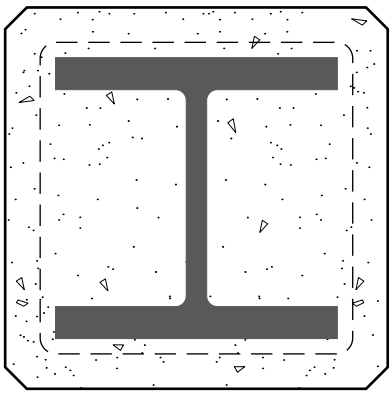


FIGURE 11.67
The relationship between temperature and strength in structural steel. *(Courtesy of American Iron & Steel Institute.)*

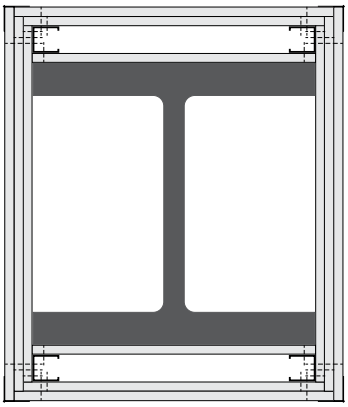
frame. The search for lighter-weight fireproofing led first to thin enclosures of metal lath and plaster around the steel members (Figure 11.70). These derive their effectiveness from the large amounts of heat needed to dehydrate the water of crystallization from the gypsum plaster. Plasters based on lightweight aggregates such as vermiculite instead of sand came into use to further reduce the weight and increase the thermal insulating properties of the plaster.

Today, options for fire-protection materials are lighter still. Plaster fireproofing has largely been replaced by beam and column enclosures made of boards or slabs of gypsum or other fire-resistant materials. These are fastened mechanically around the steel shapes, and in the case of gypsum board fireproofing, they can also serve as the finished surface on the interior of the building (Figures 11.68, 11.69, 11.71, and 11.72).

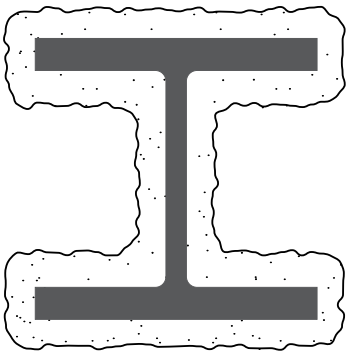
Where the fireproofing material need not serve as a finished surface, *spray-applied fire-resistive materials* (*SFRM*), commonly referred to as *spray-applied fireproofing*, have become the most prevalent type. These are mixtures of portland cement or



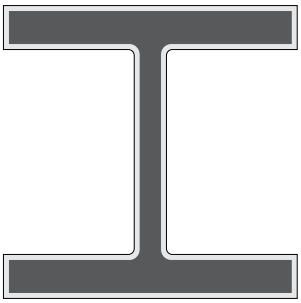
CONCRETE ENCASED



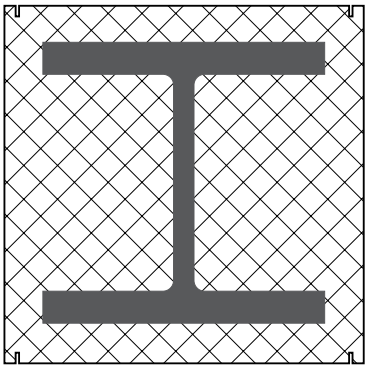
FIRE-RESISTANT BOARD ENCLOSURE



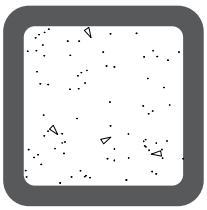
SPRAY-APPLIED FIRE-RESISTIVE MATERIAL (SFRM)



INTUMESCENT COATING



INSULATION AND METAL COVER



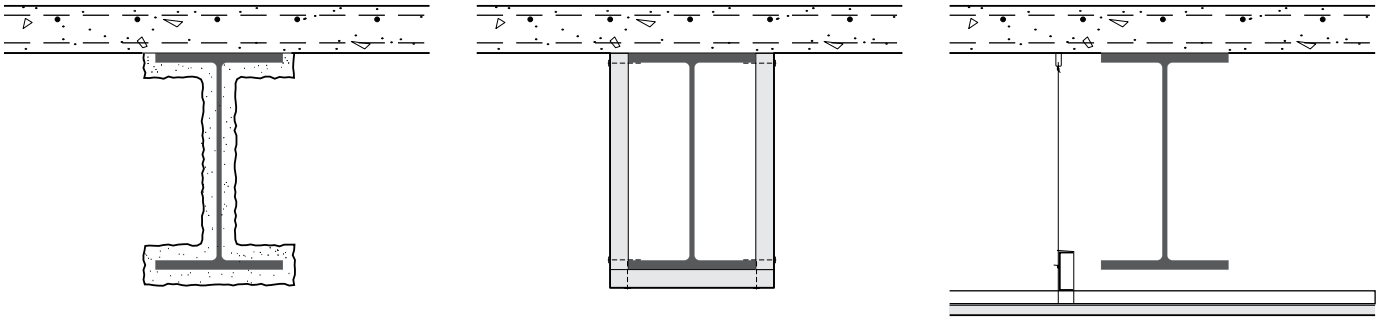
CONCRETE FILLED

FIGURE 11.68

Methods for fire-protecting steel columns. While heavier than other options, concrete encasement may be used, adding both structural capacity and fire resistance. Fire-resistant board enclosures can consist of Type X gypsum wallboard, as shown here, or other fire-resistant board products. Spray-applied fire-resistive material is the most prevalent type of fire protection. Usually, it is concealed behind finish materials. Intumescent coatings are thinner than other options and can be left exposed in the finished construction. Structural members protected with proprietary insulation products and finish metal covers are provided as prefabricated assemblies by some manufacturers. HSSs can be filled with concrete, extending their fire resistance by increasing the thermal mass of the combined materials.

gypsum and mineral wool, quartz, perlite, or vermiculite that are sprayed or troweled over the steel to the required thickness (Figures 11.68, 11.69, 11.73, and 11.74). These products are available in densities ranging from about 12 to 40 pounds per cubic foot (190 to 640 kg/m^3). The lighter materials are fragile and always concealed behind other finish materials. The denser materials are more durable and are sometimes left exposed, for example in mechanical rooms or other utilitarian spaces. All spray-applied materials act primarily by insulating the steel from high temperatures. They are usually applied in the field after the steel has been erected and the connections between members completed. Less frequently, they may be applied in the fabrication shop, where controlled environmental conditions and easier access to the steel members can result in faster application and more consistent quality.

In buildings with floors higher than 75 feet (23 m) above ground, the International Building Code (IBC) requires spray-applied fireproofing with higher bond strengths, to make it less likely that these materials may be dislodged from the structural members they protect in the event of an unusual event, such as the airplane attacks on the Manhattan



SPRAY-APPLIED FIRE-RESISTIVE MATERIAL (SFRM)

FIRE-RESISTANT BOARD ENCLOSURE

SUSPENDED FIRE-RESISTANT CEILING

FIGURE 11.69

Methods for fireproofing steel beams and girders. Spray-applied fire-resistive material is the most prevalent. The fire-resistant board enclosure shown here is an insulating mineral board. A suspended fire-resistant ceiling is one example of *membrane fire protection*, in which the fire-protection material is not directly attached to the steel member. A gypsum board ceiling is shown here. Plaster and other types of mineral boards or tiles can also be used. Only secondary framing members, such as beams spanning between girders or bearing walls, are permitted to be protected in this manner. Primary framing members, such as most columns, and the beams and girders that frame directly into columns, must be protected with materials directly applied to the member.

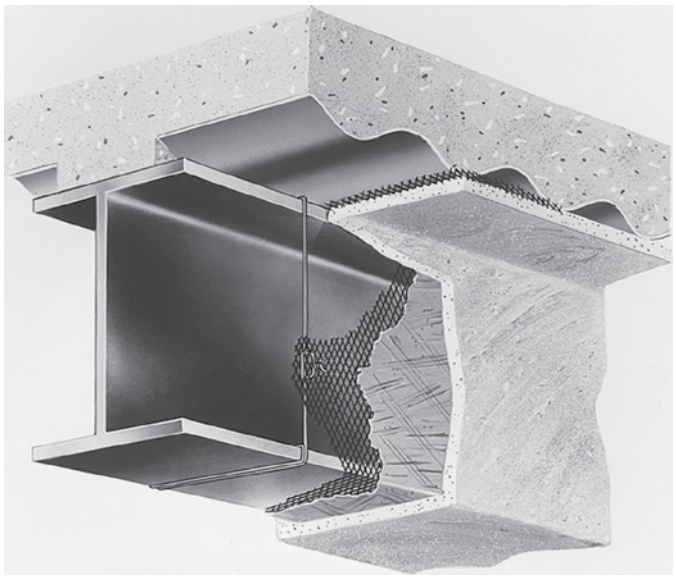


FIGURE 11.70

Lath-and-plaster fireproofing around a steel beam. *(Courtesy of United States Gypsum Company.)*

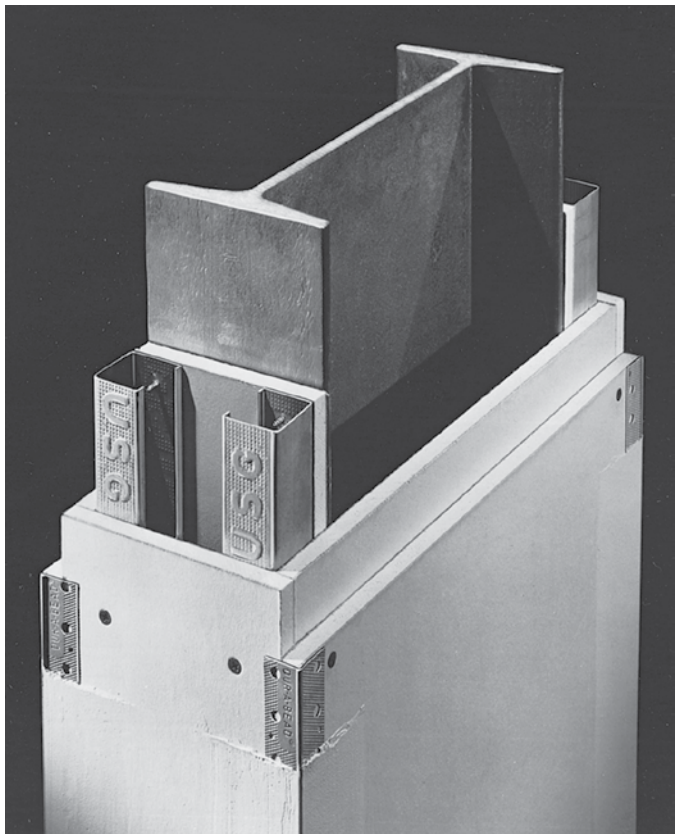


FIGURE 11.71

Gypsum board fireproofing around a steel column. The gypsum board layers are screwed to the four cold-formed steel C-channels at the corners of the column, and finished with steel corner bead and drywall compound on the corners. *(Courtesy of United States Gypsum Company.)*

Figure 11.72
Attaching slab fireproofing made of mineral fiber to a steel column, using welded attachments. *(Courtesy of United States Gypsum Company.)*

Figure 11.73
Applying spray-on fireproofing to a steel beam, using a gauge to measure the depth. *(Courtesy of W. R. Grace & Co.)*

Figure 11.74
In this photograph, spray-applied fireproofing appears as a light-colored, lumpy coating on steel members. Note that the diagonal bracing remains unprotected. Structural members that serve only to resist lateral forces (but not gravity loads) are not required to be fireproofed. The braces in this photograph are *buckling-restrained braces*, designed to provide both lateral stability and structural damping. Within the brace, a relatively slender steel core is encased in grout and surrounded by the square steel casings visible in the photograph. In an extreme seismic event, the inner core experiences repeated plastic elongation and compression, absorbing dynamic energy imparted into the building structure and lessening the stresses experienced by other parts of the frame. *(Photo by Joseph Iano.)*

World Trade Center towers that occurred in 2001. *Intumescent mastics* and *intumescent paints* (Figure 11.68) are thin paint-like coatings that allow steel structural elements to remain exposed to view in situations of low-to-moderate fire risk. They expand when exposed to fire to form a thick, stable char that insulates the steel from the heat of the fire for varying lengths of time, depending on the thickness of the coating and the weight of the steel member.

Longer Spans and Higher-Capacity Columns in Steel

Standard wide-flange beams are suitable for the range of structural spans normally encountered in offices, schools, hospitals, apartment buildings, hotels, retail stores, warehouses, and other buildings in which columns may be brought to earth at intervals without obstructing the activities that take place within. For many other types of buildings—athletic buildings, some industrial buildings, aircraft hangars, auditoriums, theaters, religious buildings, transportation terminals—longer spans are required than can be accomplished with wide-flange beams. A rich assortment of longer-span structural devices is available in steel for these uses.

Improved Beams

The *castellated beam* (Figures 11.75 and 11.76) is produced by flame-cutting the web of a wide-flange section along a zigzag or arced path, then reassembling the beam by welding its two halves point to point, thus increasing its depth without increasing its weight. This greatly augments the spanning potential of the beam, provided that the superimposed loads are not exceptionally heavy. The ubiquitous openings in castellated beams can also facilitate the routing of various building services within the floor/ceiling space.

For long-span beams tailored to any loading condition, *plate girders* are custom-designed and fabricated. Steel plates and angles are assembled by bolting or welding in such a way as to put the steel exactly where it is needed: The flanges are often made thicker in the middle of the span where bending forces are higher, more web stiffeners are provided near the ends where web stresses are high, and areas around the supports are specially reinforced. Almost any depth can be manufactured as needed, and very long spans are possible, even under heavy loads (Figure 11.77). These members are often tapered, having greater depth where the bending forces are largest.

Rigid steel frames are efficiently produced by welding together steel wide-flange sections or plate girders. They may be set up in a row to roof a rectangular space (Figure 11.78) or arrayed around a vertical axis to cover a circular area. Their structural action lies midway between that of a rectilinear frame and that of an arch. Like an arch, they may sometimes require steel tie rods at the base to resist lateral thrust, in which case these rods are usually concealed within the floor slab.

Castellated beams, plate girders, and rigid steel frames share the characteristic that because they are long, slender elements, and they frequently must be braced laterally by purlins, girts, decking, or diagonal bracing to prevent them from buckling.

Trusses

Steel trusses are triangular arrangements of steel members that are generally deeper and lighter than improved beams and can span correspondingly longer distances. They can be designed to carry light or heavy loads. Earlier in this chapter, open-web joists and joist girders were presented. These are standardized trusses made from light members. They can span further than conventional steel framing systems while still remaining less expensive than longer-spanning custom-made trusses.

Custom-designed and fabricated roof trusses for light loadings are traditionally made up of steel tee or paired-angle top and bottom *chords* with paired-angle internal members. The angles within each pair are spaced just far enough apart to leave space between for the steel gusset plate connectors that join them to the other members

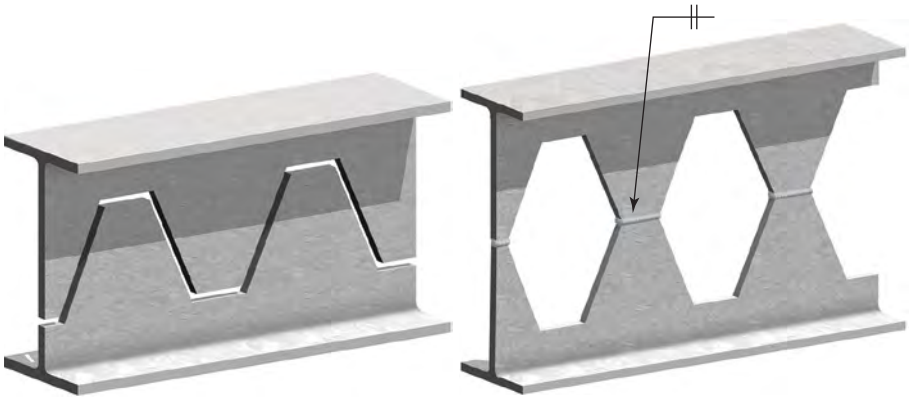


Figure 11.75
Manufacture of a castellated beam.

FIGURE 11.76
A long-span floor system is framed with castellated beams in this four-story office building. *(Photo by Joseph Iano.)*

FIGURE 11.77
Erecting a welded steel plate girder. Notice how the girder is custom-made with cutouts for the passage of pipes and ductwork. The section being erected is 115 feet (35 m) long, 13 feet (4 m) deep, and weighs 192,000 pounds (87,000 kg). *(Courtesy of Bethlehem Steel Corporation.)*

Figure 11.78
The steel rigid frames of this industrial building carry steel *purlins* that will support the roof deck and *girts* to support the wall cladding. The depth of each frame varies with the magnitude of the bending forces and is greatest at the eave connections, where these forces are at a maximum. *(Courtesy of Metal Building Manufacturers Association.)*

of the truss. They may be either welded or bolted to the gusset plates (Figures 11.79).

Trusses for heavier loadings, such as for very-long-span roofs or the lateral transfer of column loads in a tall building where columns from floors above are interrupted by a large, open space lower in the building, can be made from virtually any type of larger section structural members (Figure 11.80). Where long-span trusses remain exposed in the finished building, their design and detailing frequently become important architectural elements (Figure 11.81).

The *staggered truss system* (Figure 11.64) relies on story-high steel trusses, staggered on alternating floors of a building structure, and spanning between perimeter columns, to support the floors and roof. Typically, the trusses are concealed within partitions, leaving the remaining floor areas column free. The depth of the floor structure in a staggered truss building is only as much as the thickness of the decking system itself, resulting in overall floor-to-floor heights of as little as 8 feet 8 inches (2.6 m). An additional advantage is that the ground-floor level can be made completely free of columns or other interior structural members. (The first floor above grade is supported by trusses spanning between it and the next level above grade.)

A steel *space truss* (or *space frame*) is a truss made three dimensional (Figure 11.82). It carries its load by bending along both of its axes, much like a two-way concrete slab (Chapter 13). It must be supported by columns that are spaced more or less equally in both directions.

Arches

Short-span steel *arches* can be made by bending standard wide-flange

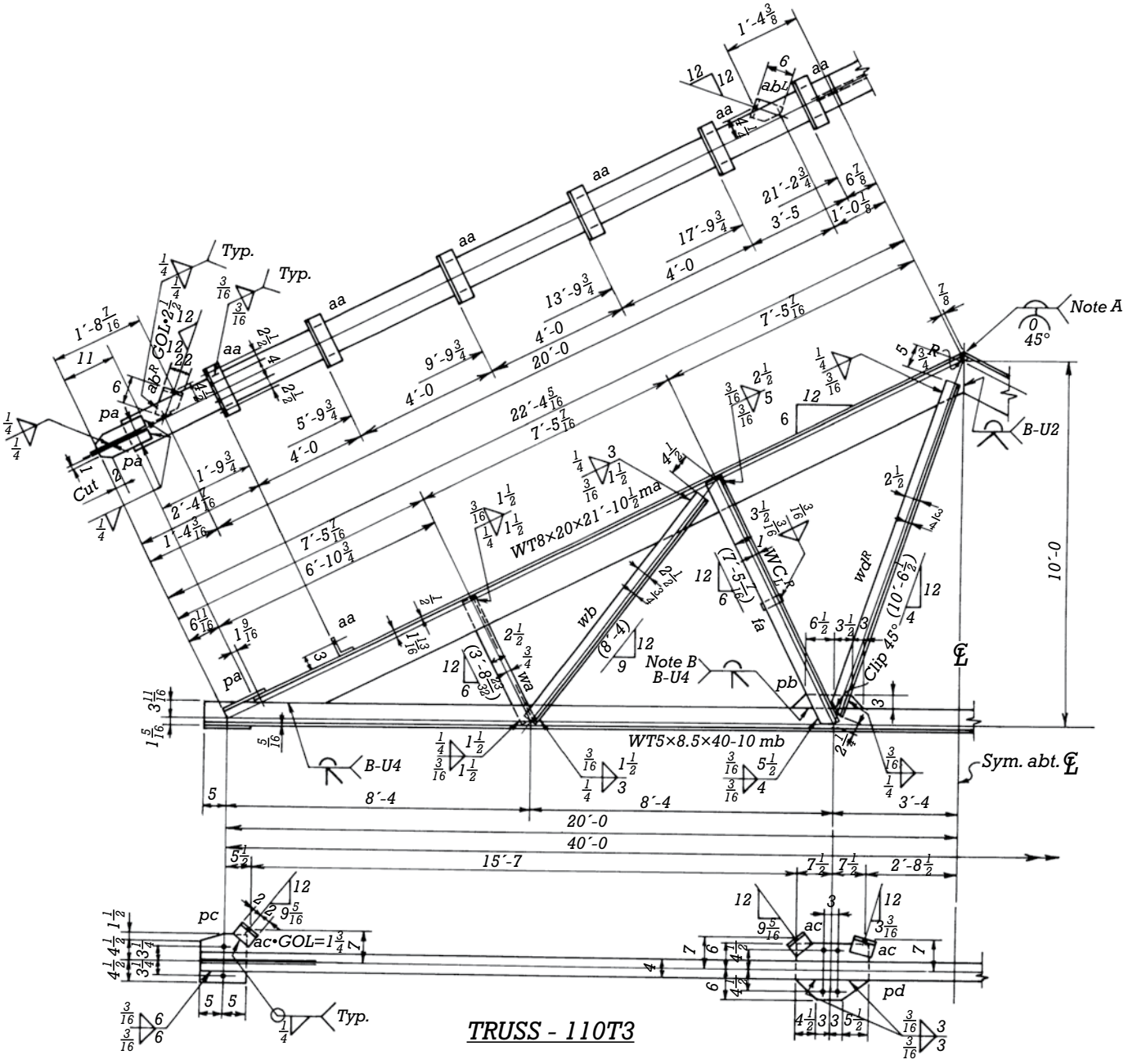


Figure 11.79

A fabricator's shop drawing of a welded steel roof truss made of tees and paired-angle diagonals. *(Reprinted with permission of the American Institute of Steel Construction from* Detailing for Steel Construction, *1983. Chicago: AISC.)*

Figure 11.80
Ironworkers seat the end of a heavy roof truss made of wide-flange sections. *(Permission of the American Institute of Steel Construction.)*

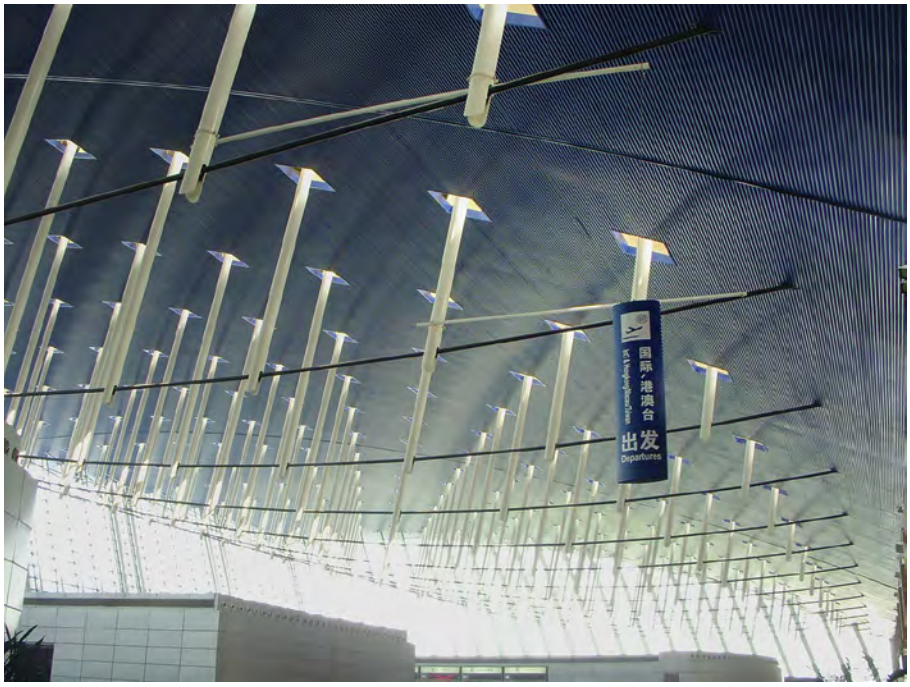


Figure 11.81
Steel lenticular trusses supporting the roof of the Shanghai Pudong Airport passenger terminal. The truss upper chords are concealed above the finish ceiling. The steel cable lower chords and struts connecting the top and bottom chords create a strong visual pattern within the space. *(Photo by Joseph Iano.)*

Figure 11.82
Assembling a space truss. *(Courtesy of Unistrut Space-Frame Systems, GTE Products Corp.)*

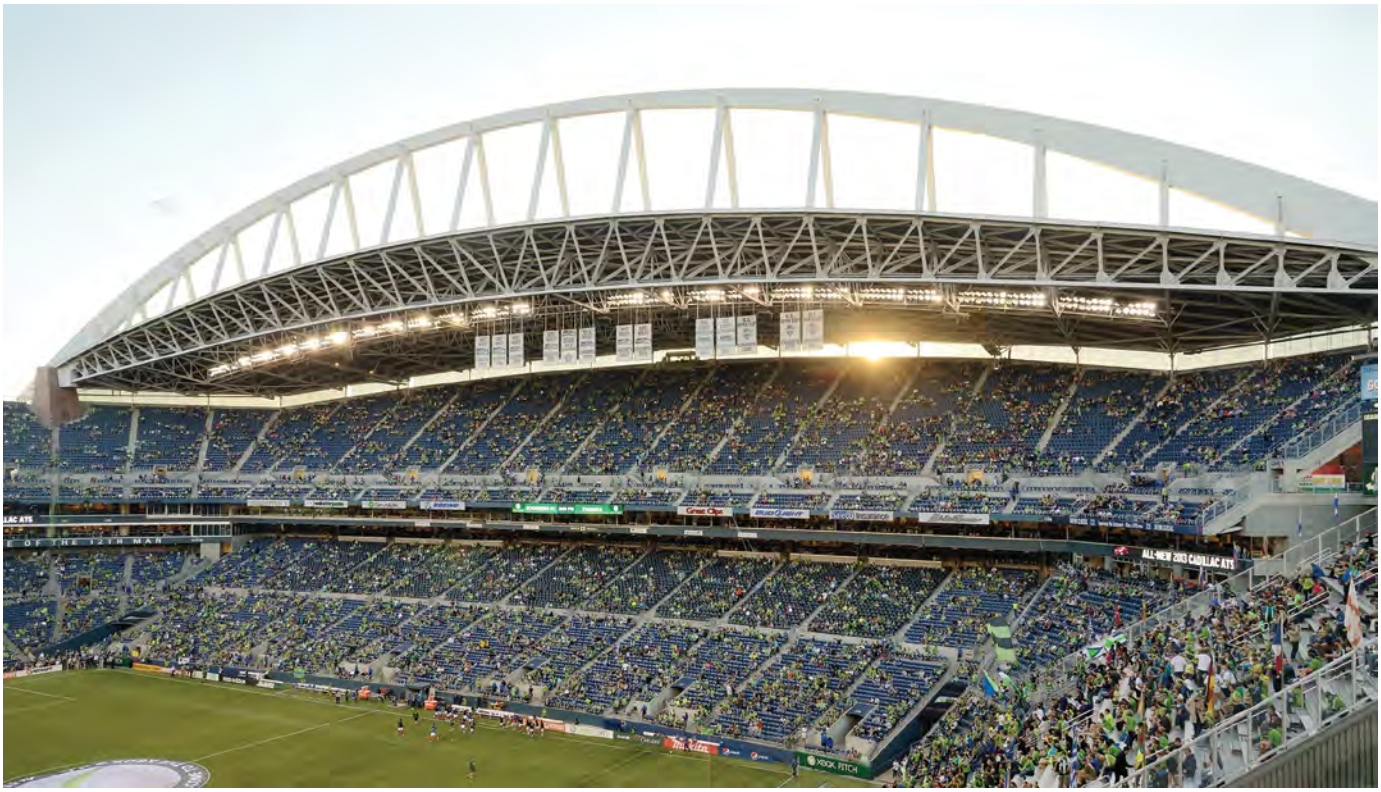


Figure 11.83
A steel roof arch at Century Link Field, Seattle, spans more than 700 feet (215 m). The thrust of the arch is resisted by high-tensile-strength cables that are just visible within the roof trusswork underneath the arch. *(Photo by Joseph Iano.)*

shapes or by joining sections of straight members. When the truss form is extruded or rotated, vaults and domes can also be made. Heavier arches are one of the longest-span structural forms available to the building designer. Lateral thrusts are produced at the base of any arch and must be resisted by the foundations, or with a cable, tie rod, or other structural member that connects opposite ends of the arch (Figure 11.83).

Tensile Structures

Fabrics and cables made of cold-drawn, high-tensile-strength steel wire are the material for a fascinating variety of tentlike roofs that can span from short to very long distances. With *anticlastic* (saddle-shaped) *curvature*, *cable stays*, or other means of restraining the cable net, hanging roofs are fully rigid against wind uplift and flutter. For smaller spans, fabrics can do most of the work, supported by steel cables along the edges and at points of maximum stress (Figure 11.84), as presented in the accompanying sidebar.

The spider web is a good inspiration for steel construction.

—Frank Lloyd Wright, "In the Cause of Architecture: The Logic of the Plan," *Architectural Record*, January 1928

Figure 11.84
The Olympic Stadium roof in Munich, Germany, is made of steel cables and transparent acrylic plastic panels. For scale, notice the worker seen through the roof at the upper left. *(Architects: Frei Otto, Ewald Bubner, and Behnisch & Partner. Courtesy of Institute for Lightweight Structures, Stuttgart.)*

Fabric Structures

Fabric structures are not new: People have constructed tents since the earliest days of human civilization. Today, new, durable fabrics and computerized methods for finding form and forces have helped to create a new construction type: a permanent, rigid, stable fabric structure that will last for 20 years or more.

Types of Fabric Structures

Fabric structures are either tensile or pneumatic (Figure A). A *tensile fabric structure* is a membrane supported by masts or other rigid structural elements such as frames or arches. The membrane usually consists of a woven textile fabric reinforced with steel cables along the main lines of stress. The fabric and cables transmit external loads to the rigid supports and ground anchors by means of tensile forces.

Pneumatic structures depend on air pressure for their stability and their capacity to carry snow and wind loads. The most common type of pneumatic structure is the *air-supported structure*, in which an airtight fabric, usually reinforced with steel cables, is held up by pressurizing the air in the inhabited space below it. The fabric and cables in an air-supported structure are stressed in tension.

Fabrics for Permanent Structures

The fabrics used in fabric structures are of two general types: coated structural fabrics or polymer film. Coated structural fabrics consist of a woven cloth that provides strength and a coating that makes the fabric airtight and water resistant. The two most widely used are polyester cloth laminated or coated with polyvinyl chloride (PVC) and glass fiber cloth coated with polytetrafluorethylene (PTFE, the most common brand of which is known as Teflon). The PVC/polyester fabric is the more economical. It is fire-resistant, but not fully noncombustible, limiting its use for some applications. PTFE-coated glass fiber cloth is noncombustible, has a longer life span, and remains cleaner for longer periods of time. Ethylene tetrafluoroethylene (ETFE) is a thin, extruded polymer film that is lightweight, fire-retardant, and highly transparent. All three fabrics are highly resistant to the deteriorating effects of ultraviolet light, oxidation, and fungi.

Fabrics may be white, colored, tinted, or imprinted with patterns or graphics. A fabric may be totally opaque; translucent, allowing a controlled percentage of light to pass through; or, in the case of ETFE, virtually transparent.

Though a single layer of fabric has little resistance to the flow of heat, a properly designed fabric structure can achieve substantial energy savings over conventional enclosures through selective use of translucency, reflectivity, and air-insulating strategies. Translucency can be used to provide natural illumination, gather solar heat in the winter, and cool the space at night in the summer. A highly reflective fabric can reduce solar heat gain and conserve artificial illumination. With the addition of a second layer, a fabric liner that is suspended about a foot (300 mm) below the structural fabric, the thermal resistance of the structure can be improved. Or in the case of ETFE, double- or triple-layer pneumatic cushions can be created to provide thermal resistance. An acoustic inner liner can help to control internal sound reflection, which is especially important in air-supported structures, which tend to focus sound. Tensile structures, because of their anticlastic curvature, tend to disperse sound rather than focus it.

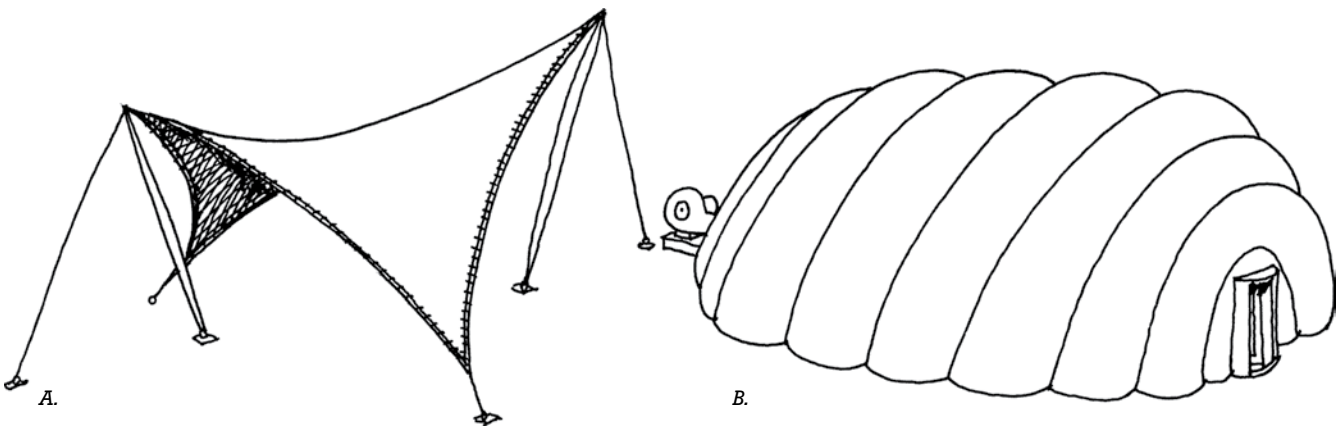


Figure A
Simple tensile (*A*) and (*B*) pneumatic (air-supported) fabric structures. *(Sketch by Edward Allen.)*

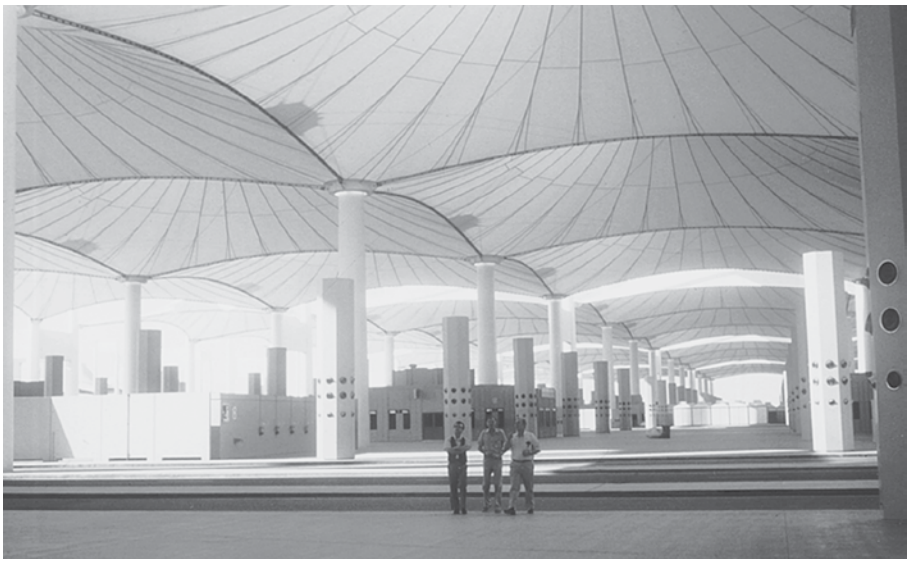
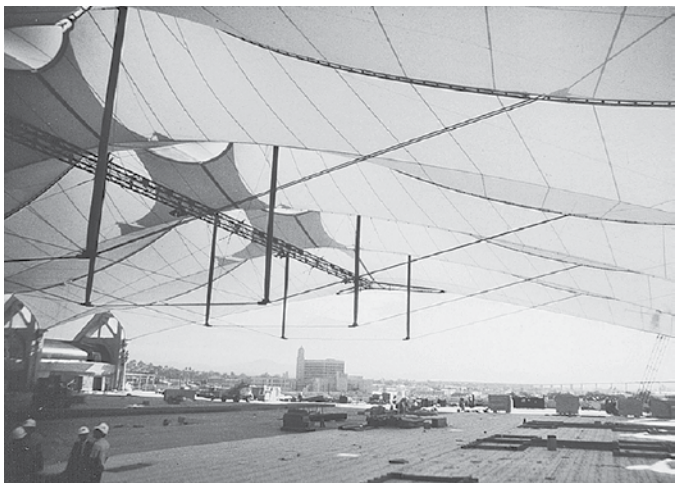


FIGURE B
One of the world's largest roof structures covers the Haj Terminal in Jeddah, Saudi Arabia, an airport building that is used to facilitate the travel of vast numbers of Muslim faithful during a short period of annual pilgrimage. The roof is made up of radial shapes. *(Architect: Skidmore, Owings & Merrill. Roof designer and structural engineer: Geiger Berger Associates. Photos for Figures B–E courtesy of the photographer, Horst Berger.)*

FIGURE C
The fabric of the Haj Terminal is PTFE-coated glass fiber cloth.

FIGURE D
The roof canopy of the San Diego Convention Center is supported at the perimeter on the concrete frame of the building below.

FIGURE E
The San Diego Convention Center's roof is raised at the middle on rigid steel struts that rest on cables supported by the concrete frame. *(Architect: Arthur Erickson Associates. Roof designer and structural engineer: Horst Berger.)*



Fabric Structures (continued)

Tensile Structures

Tensile structures are stabilized by anticlastic curvature and prestress. Anticlastic curvature means that the fabric is curved simultaneously in two opposite directions. Two basic geometries may be used: One is the saddle shape (Figures D and E), the other the radial tent (Figures B and C). It is from combinations and variations of these geometries that all tensile structures are shaped.

Prestress is the introduction of permanent tension into the fabric in two opposing directions. Without anticlastic curvature and prestress, the fabric would flutter in the wind and destroy itself within a short time. The amount of curvature and the amount of prestressing force must both be sufficient to maintain stability under expected wind and snow conditions. If the curvature is too flat or if the prestressing tension is too low, excessive deflection or flutter will occur.

The design of a tensile structure usually begins by experimenting with simple physical models. These often are made of pantyhose material or stretch fabric, either of which is easily stretched and manipulated. After a general shape has been established with the model, a computer is used to find the exact equilibrium shape, determine the stresses in the fabric and supporting members under wind and snow loadings, and generate cutting patterns for the fabric. The design process is referred to as *form finding*, because a tensile structure cannot be made to take any arbitrary shape. Just as a hanging chain will always take a form that places its links in equilibrium with one another, a tensile structure must take a form that maintains proportionate amounts of tension in all parts of the fabric under all expected loading conditions. The designer's task is to find such a form.

A good design for a tensile structure employs short *masts* to minimize buckling problems. The fabric generally cannot come to a peak at the mast, but must terminate in a cable ring that is attached to the mast in order to avoid high tensile stresses in the fabric. The perimeter edges of the fabric usually terminate along curving steel cables. To make a stable structure, these cables must have adequate curvature and must be anchored to foundations that offer firm resistance to uplift forces. The fabric may be attached to the cables by sleeves sewn into the edges of the fabric or clamps that grip the fabric and pull it toward the cable.

Air-Supported Structures

Air-supported structures are pressurized by the fans that are used to heat, cool, and ventilate the building. The required air pressures are so low that they are scarcely discernible by people entering or leaving the building, but they are high enough (5 to 10 pounds per square foot, or 0.25 to 0.50 kPa) to prevent ordinary swinging doors from opening. For this reason, revolving doors, whose operation is unaffected by internal pressure and that maintain a continual seal against loss of air, are usually used for access.

The fabric of an air-supported structure is prestressed by its internal air pressure to prevent flutter. For low-profile roof shapes, a cable net is employed to resist the high forces that result from the flat curvature. The fabric spans between the cables. The fabric and cables pull up on the foundations with a total force that is equal to the internal air pressure multiplied by the area of ground covered by the roof. The supporting elements and foundations must be designed to resist this force.

Wind causes suction forces to occur on many areas of an air-supported structure, which results in additional tension in the fabric and cables. The downward forces from wind or snow load on an air-supported structure must be resisted directly by the internal air pressure pushing outward against them. In geographic areas where snow loads are larger than acceptable internal pressures, snow must be removed from the roof. Failure to do so has led to unplanned deflations of several air-supported roofs.

In theory, air-supported structures are not limited in span. In practice, flutter and perimeter uplift forces restrict their span to a few hundred meters, but this is sufficient to house entire football stadiums. For safety, the outer edges of most air-supported roofs terminate at a level that is well above the floor level within. Thus, if the roof deflates because of fan failure, inadequate snow removal, or air leakage, the roof fabric will hang in suspension at a height well above the floor of the building (Figure F).

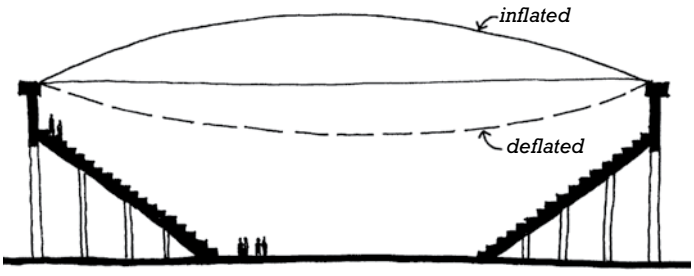


Figure F

Most air-supported structures are designed so that if air pressure fails, the membrane will hang at a safe level above the heads of the occupants. *(Sketches by Edward Allen.)*

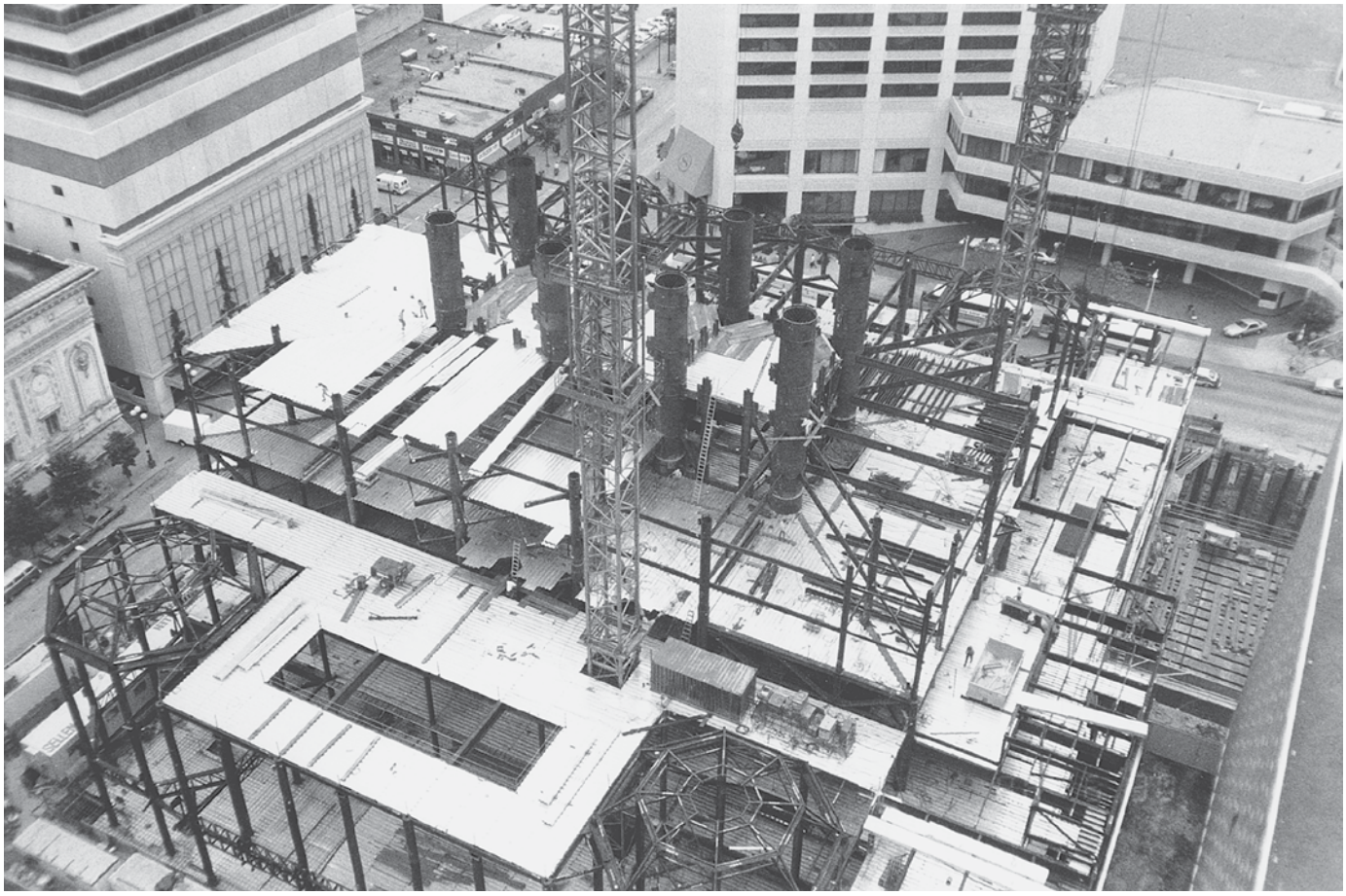


Figure 11.85
A core structure of eight large composite columns, each a concrete-filled pipe 7½ feet (2.3 m) in diameter, carries the majority of gravity and wind loads in this 44-story Seattle office building. The perimeter of the building is supported by smaller-diameter composite pipe columns. *(Courtesy of Skilling Ward Magnusson Barkshire, Inc., Seattle, WA, Consulting Structural & Civil Engineers.)*

Composite Columns

Steel and concrete can be combined in various ways to make *composite columns*. Sitecast reinforced concrete may be cast around steel wide-flange columns, or steel pipe may be filled with concrete. Or, a wide-flange column may be inserted within a pipe before the concrete is added to achieve a higher loadbearing capacity.

Especially in tall buildings, large steel pipe columns filled with very-high-strength concrete may be used to carry large vertical and lateral loads. These columns enable reductions of as much as 50 percent in the overall quantity of steel required for the building (Figure 11.85). One example is a 720-foot (200-m) tall office tower, in which four 10-foot (3-m) diameter pipe columns filled with 19,000-psi (131-MPa) concrete carry 40 percent of the building's gravity loads and a large proportion of the wind loads. There is no reinforcing or other steel inside the pipes except at certain highly stressed connections. Composite columns in tall buildings reduce steel usage, stiffen the building against wind forces, and simplify beam–column connections.

Sustainability and Steel Frame Construction

Energy Performance

• Steel framing members in building walls and roofs should be thermally broken or insulated to minimize thermal bridging and wasteful heat losses between indoors and outdoors.

Building and Material Life-Cycle Impacts

• An American Institute of Steel Construction EPD reports the following industry average cradle-to-gate impacts for one metric ton (2200 lb) of fabricated hot-rolled structural steel:

Nonrenewable primary energy consumption	15,000 MJ (14 million BTU)
Global warming potential	1200 kg (2600 lb) CO_2 eq.

• A Steel Deck Institute EPD reports the following industry average cradle-to-gate impacts for one metric ton (2200 lb) of corrugated steel roof and floor deck panels:

Nonrenewable primary energy consumption	29,000 MJ (27 million BTU)
Global warming potential	2400 kg (5200 lb) CO_2 eq.
Fresh water consumption	23,000 L (6100 gal)

• Ninety-five percent or more of all structural steel used in North American building construction is eventually recycled or reused—a very high rate.

Material and Production Attributes

• The manufacture of a ton of steel from iron ore by the basic oxygen process consumes 3170 pounds (1440 kg) of ore, 300 pounds (140 kg) of limestone, 900 pounds (410 kg) of coke (made from coal), 80 pounds (36 kg) of oxygen, and 2575 pounds (1170 kg) of air. In the process, 4550 pounds (2070 kg) of gaseous emissions are given off, and 600 pounds (270 kg) of slag and 50 pounds (23 kg) of dust are generated. Further emissions emanate from the process of converting coal to coke.

• The ore, coal, and limestone are minerals whose mining and quarrying cause disruption of land and loss of wildlife habitat, often coupled with pollution of streams and rivers. Coal, limestone, and low-grade iron ore are plentiful, but high-grade iron ore has been depleted in many areas of the earth.

• Supplies of some alloying metals, such as manganese, chromium, and nickel, are becoming depleted.

• In North America, virtually all hot-rolled structural steel shapes are manufactured by the electric arc furnace process. The recycled content of steel manufactured by this process averages 90 percent or higher.

• Steel plate and sheet, used in the manufacture, for example, of light gauge steel members, decking, and hollow structural sections, may be produced by either the electric arc furnace or basic oxygen processes. Steel made by the basic oxygen process contains 25 to 35 percent recycled material.

• Scrap used in the production of structural steel in mini-mills usually comes from sources within approximately 300 miles (500 km) of the mill. When the steel produced is then used for the construction of buildings not too far from the mill, the steel may be eligible for credit as a regionally extracted, processed, and produced material.

Unhealthful Materials and Emissions

• Steel, itself, is not associated with indoor air quality problems.

• Surface oils and protective steel coatings can be sources of volatile organic compound emissions.

• Some spray-on fireproofing materials can pollute the air with stray fibers.

Responsible Industry Practices and Social Impacts

• Since 1990, the North American steel industry has reduced energy consumption and greenhouse gas emissions per ton of steel produced by roughly 31 and 36 percent, respectively.

Steel and the Building Codes

Steel frame construction, because it is noncombustible, can be used in any building code construction type, as long as the steel is protected against fire to the levels required for that type (Figure 1.5). Because steel is also strong and resilient, it is well suited for use in tall building structures. Together, these reasons make steel one of the most common choices for building code Type I and II buildings (Figure 1.4).

Uniqueness of Steel

Among the common noncombustible structural materials—masonry, concrete, and steel—steel alone has useful tensile strength, which, along with compressive strength, it possesses in great abundance (Figure 11.86). A relatively small amount of steel can do a structural job that would take a much greater amount of another material. Thus, steel, the densest structural material, is also the one that often produces the lightest structures and those that span the greatest distances.

The infrastructure needed to bring steel shapes to a building site—the mines, the mills, the fabricators, and the scrap metal industry—is vast and complex. An elaborate sequence of advance planning and preparatory activities is required for making a steel building frame. Once on the site, however, a steel frame goes together quickly, and with relatively few tools, in an erection process that is rivaled for speed and all-weather reliability only by certain precast concrete systems. With proper design and planning, steel can frame almost any shape of building. Ultimately, of course, structural steel produces only a frame. Unlike masonry or concrete, it does not lend itself easily to forming a complete building enclosure except in certain industrial applications. This is of little consequence, however, because steel mates easily with glass, masonry, and panel systems of enclosure and because steel does its own job, that of carrying loads high and wide, so well.

Material	Strength in Tension	Strength in Compression	Modulus of Elasticity	Density
Wood (framing lumber)	270–4100 psi (1.9–28 MPa)	1400–4400 psi (9.7–31 MPa)	1,100,000–1,900,000 psi (7600–13,000 MPa)	27 pcf (430 kg/m^3)
Brick masonry (including mortar, unreinforced)	30–80 psi (0.21–0.55 MPa)	1000–4000 psi (6.9–28 MPa)	800,000–3,000,000 psi (5500–21,000 MPa)	120 pcf (1900 kg/m^3)
Structural steel	60,000–90,000 psi (415–620 MPa)	60,000–90,000 psi (415–620 MPa)	29,000,000 psi (200,000 MPa)	490 pcf (7800 kg/ m^3)
Concrete (unreinforced)	300–700 psi 2.1–4.8 MPa	3000–6000 psi (20–40 MPa)	2,000,000–6,000,000 psi (14,000–41,000 MPa)	145 pcf (2300 kg/m^3)

Figure 11.86

Comparative ultimate strength properties of four common structural materials: wood, brick masonry, steel (shaded row), and concrete. On a volumetric basis, steel is the strongest. Wood values are for stresses parallel to the grain of the wood.

Figure 11.87
This elegantly detailed house in southern California is an early example of the use of structural steel at the residential scale. *(Architect: Pierre Koenig, FAIA. Photo by Julius Shulman, Hon. AIA.)*

Figure 11.88
Architect Peter Waldman utilized steel pipe columns, wide-flange beams, open-web steel joists, and corrugated steel roof decking for his own house in Charlottesville, Virginia. *(Photo by Maxwell MacKenzie.)*

FIGURE 11.89
(*Opposite page*) Chicago is famous for its role in the development of the steel frame skyscraper (see also Figure 11.4). One of the tallest in the United States is the Willis Tower (formerly the Sears Tower), seen in the foreground of this photograph. The lateral force resisting system is a bundled tube system, consisting of interconnected side-by-side tube structures. *(Architect and engineer: Skidmore, Owings & Merrill. Photo by Chicago Convention and Tourism Bureau, used with permission of the American Institute of Steel Construction.)*

MasterFormat Sections for Steel Frame Construction

05 12 00	**STRUCTURAL STEEL FRAMING**
05 12 13	Architecturally Exposed Structural Steel Framing
05 12 19	Buckling Restrained Braces
05 16 00	**STRUCTURAL CABLING**
05 21 00	**STEEL JOIST FRAMING**
05 21 19	Open-Web Steel Joist Framing
05 31 00	**STEEL DECKING**
05 31 13	Steel Floor Decking
05 31 23	Steel Roof Decking
05 31 33	Steel Form Decking
05 36 00	**COMPOSITE METAL DECKING**
05 56 00	**METAL CASTINGS**
07 81 00	**APPLIED FIREPROOFING**
07 81 16	Cementitious Fireproofing
07 81 23	Intumescent Fireproofing
07 81 29	Mineral-Fiber Cementitious Fireproofing
07 81 33	Mineral-Fiber Fireproofing
07 82 00	**BOARD FIREPROOFING**

KEY TERMS

Bessemer process
open-hearth method
steel
alloy
mild steel
cast iron
wrought iron
ferrous metal
iron ore
smelting
blast furnace
coke
slag
basic oxygen process
mini-mill
electric arc furnace
beam blank, bloom
high-strength, low-alloy steel
weathering steel
stainless steel
quenching
tempering
structural mill, breakdown mill
hot saw
cooling bed
roller straightener
wide-flange shape
American Standard shape, I-beam
angle
gusset plate
channel
tee
plate
barsheet
cast steel
cold-worked steel, cold-formed steel
hollow structural section (HSS)
open-web steel joist (OWSJ)
joist girder
rivet
high-strength bolt
carbon steel bolt
bearing-type connection
snug-tight
slip-critical connection, friction-type connection
preloaded (bolt)
faying surface
galling
impact wrench
turn-of-nut method
load indicator washer, direct tension indicator (DTI)
calibrated wrench method
tension-control bolt
shear wrench
lockpin and collar fastener, swedge bolt
electric arc welding
electrode
weld symbol
backup bar, backing bar
runoff bar
demand-critical weld
shear connection
shear
bending moment
framed connection
moment connection
full-penetration groove weld
stiffener plate
shear tab
lateral force resisting system (LFRS)
braced frame
diagonal bracing
Chevron bracing, inverted V bracing
crossbracing
eccentrically braced frame
shear wall
moment-resisting frame
core structure
braced core

shear core
tube structure
special seismic force resisting system
intermediate seismic force resisting system
ordinary seismic force resisting system
seismic fuse
fully restrained (FR) moment connection
partially restrained (PR) moment connection
simple connection
seated connection
end plate connection
fabricator
shop drawing
coped flange
plasma cutting
laser cutting
camber
erector
ironworker
tier
baseplate
leveling plate
grout
raising gang
plumbing up
tower crane
luffing-boom crane
hammerhead boom crane
tagline
drift pin
topping out
metal decking
form deck
composite metal deck
composite floor slab
roof deck
cellular deck
arc spot weld, puddle weld
arc seam weld
composite beam
shear stud
architecturally exposed structural steel (AESS)
fireproofing, fire protection
membrane fire protection
spray-applied fire-resistive materials (SFRM), spray-applied fireproofing
buckling-restrained bracing
intumescent mastic
intumescent paint
castellated beam
plate girder
rigid steel frame
purlin
girt
steel truss
chord
staggered truss system
space truss, space frame
arch
anticlastic curvature
cable stay
tensile fabric structure
pneumatic structure
air-supported structure
prestress
form finding
mast
composite column

Review Questions

1. What is the difference between iron and steel? What is the difference between wrought iron and cast iron?

2. By weight, what is the major raw material used in the making of cast iron?

3. How are steel structural shapes produced? How are the weights and thicknesses of a shape changed?

4. How does the work of the fabricator differ from that of the erector?

5. Explain the designation W21 × 68.

6. How can you tell a shear connection from a moment connection? What is the role of each?

7. Why might a beam be coped?

8. What is the advantage of composite construction?

9. Explain the advantages and disadvantages of a steel building structure with respect to fire. How can the disadvantages be overcome?

10. List three different structural systems in steel that might be suitable for the roof of an athletic fieldhouse.

Exercises

1. For a simple multistory office building of your design:

   a. Draw a steel framing plan for a typical floor.

   b. Draw an elevation or section showing a suitable method of making the building stable against lateral forces—wind and earthquake.

   c. Make a preliminary determination of the approximate sizes of the decking, beams, and girders.

   d. Sketch details of the typical connections in the frame, using actual dimensions from the *Steel Construction Manual* (see references for this chapter) for the member size you have determined and work to scale.

2. Select a method of fireproofing, and sketch typical column and beam fireproofing details for the building in Exercise 1.

3. What fire resistance ratings in hours are required for the following elements of a steel-framed department store, three stories in height, unsprinklered, with 21,000 square feet of area per floor? (The necessary information is found in Figures 1.4 and 1.5.)

   a. Lower-floor columns

   b. Floor beams

   c. Roof beams

   d. Interior nonbearing walls and partitions

4. Find a steel building frame under construction. Observe the connections carefully and figure out why each is detailed as it is. If possible, arrange to talk with the structural engineer of the building to discuss the design of the frame.

Selected References

Ambrose, James, and Patrick Tripeny. *Simplified Design of Steel Structures* (8th ed.). Hoboken, NJ, John Wiley & Sons, 2007.

This is an excellent introduction to the calculations needed for designing and specifying steel beams, columns, and connections.

American Institute of Steel Construction. *Steel Construction Manual*. Chicago, updated regularly.

This is the bible of the steel construction industry in the United States. It contains detailed tables of the dimensions and properties of all standard rolled steel sections, data on standard connections, and specifications and code information.

American Iron and Steel Institute. *Specification for Structural Steel Buildings*. Washington, DC, updated regularly.

This specification, included in the *Steel Construction Manual*, can also be viewed for free on the American Institute of Steel Construction's website, www.aisc.org.

Ruddy, John L. et al. *Design Guide 19: Fire Resistance of Structural Steel Framing*. Chicago, AISC, 2003.

This publication includes building code requirements, fire-protection materials and methods, and standard fire resistance tests.

Websites

American Institute of Steel Construction (AISC): www.aisc.org

American Iron and Steel Institute: www.steel.org

Birdair Tensile Architecture: www.birdair.com

Nucor Steel: www.nucor.com

Research Council on Structural Connections: www.boltcouncil.org

Steel Joist Institute (SJI): www.steeljoist.org

Steel Recycling Institute: www.steelsustainability.org

Vulcraft Group: www.vulcraft.com

12

Light Gauge Steel Frame Construction

- The Concept of Light Gauge Steel Construction

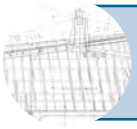
Sustainability and Light Gauge Steel Framing

- Light Gauge Steel Framing
- Other Uses of Light Gauge Steel Framing

Preliminary Design of Light Gauge Steel Frame Structures

- Insulating Light Gauge Steel Frame Structures
- Finishes for Light Gauge Steel Framing
- Advantages and Disadvantages of Light Gauge Steel Framing
- Light Gauge Steel Framing and the Building Codes

Metals in Architecture



Case Study: Camera Obscura at Mitchell Park, Greenport, New York

Driving self-drilling, self-tapping screws with electric screw guns, framers add diagonal bracing straps to a wall framed with light gauge steel studs and runner channels. *(Courtesy of United States Gypsum Company.)*

To manufacture the members used in *light gauge steel* frame construction, steel sheet is fed from continuous coils through machines at room temperature that cold-work the metal (see Chapter 11) and fold it into efficient structural shapes, producing linear members that are stiff and strong. Thus, these members are referred to as *cold-formed metal framing*, to differentiate them from much heavier hot-rolled structural steel shapes. The term "light gauge" refers to the relative thinness (gauge) of the steel sheet from which the members are made.

The Concept of Light Gauge Steel Construction

Light gauge steel construction is the noncombustible equivalent of wood light frame construction. The external dimensions of the standard sizes of light gauge members correspond closely to the dimensions of the standard sizes of nominal 2-inch (38-mm) framing lumber. These steel members are used in framing as closely spaced studs, joists, and rafters in much the same way as wood light frame members are used, and a light gauge steel frame building may be sheathed, insulated, wired, and finished inside and out in the same manner as a wood light frame building.

The steel used in light gauge members is manufactured to ASTM standard A1003 and is metallic-coated with zinc or aluminum-zinc alloy to protect against corrosion. The thickness of the metallic coating can be varied, depending on the severity of the environment in which the members will be placed. Or, in protected, noncorrosive environments, other coatings may also be used.

For wall, floor, and roof framing, the steel is formed into C-shaped *stud/joist sections* (Figure 12.1). The webs of these members may be punched at the factory to provide holes at 2-foot (600-mm) intervals to allow wiring, piping, and bracing to pass through without the necessity of cutting holes in members on the construction site (Figures 12.11 and 12.15). *Track sections* are used for top and bottom plates. They are slightly oversized so that stud/joist members can nest into them. *Channel sections* and *furring channels* are used for lighter bracing and framing tasks. Other specialized shapes are also available.

The strength and stiffness of a member depend on its shape and size, as well as the strength and thickness of sheet metal used in its manufacture. The range of metal thicknesses available for both loadbearing and nonbearing members are listed in Figure 12.2. Steel with yield strengths of both 33,000 and 50,000 psi (230 or 350 MPa) is used. Loadbearing members are used for floor and roof framing, framing of walls supporting floors or roofs, and framing that supports exterior cladding systems (because they are subject to wind loads). Nonloadbearing members are used to frame walls that do not support floor or roof loads, such as interior partitions, as well as ceilings and soffits. Loadbearing light gauge steel members are manufactured according to ASTM standard C955,

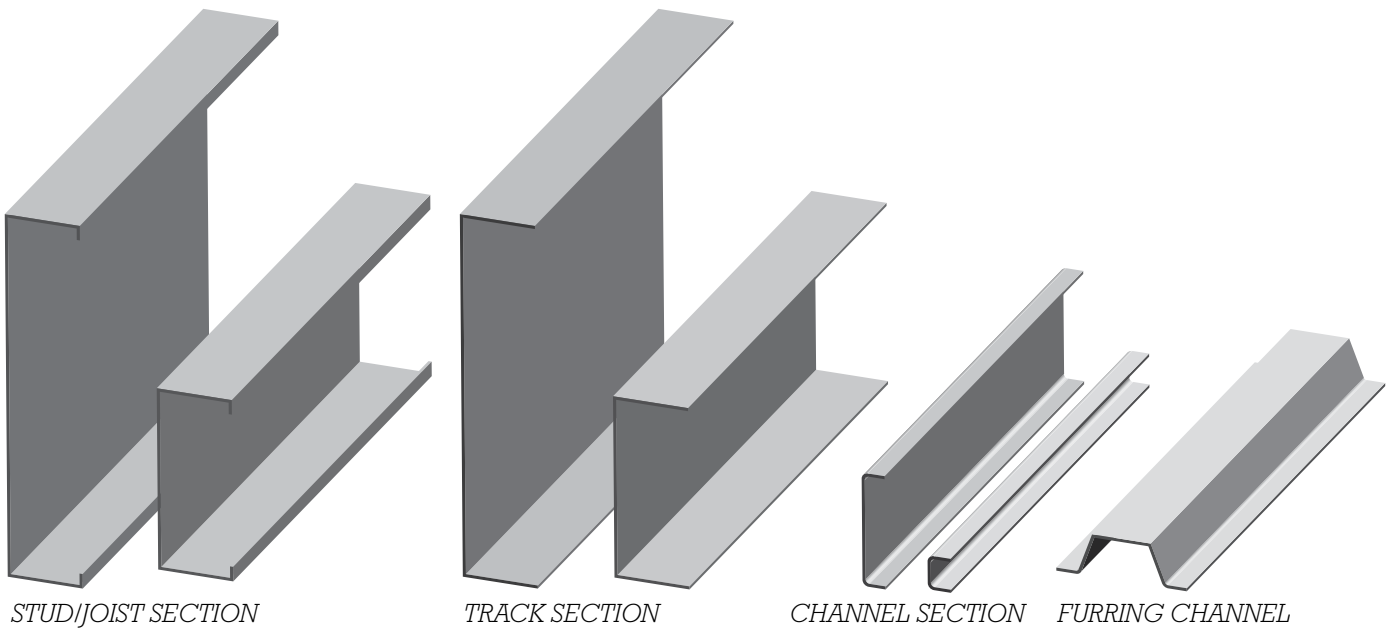


Figure 12.1
Light gauge steel framing member shapes.

Sustainability and Light Gauge Steel Framing

For more information about the sustainability of steel in building construction, see Chapter 11.

Energy Performance

- Light gauge steel framing members have a high thermal conductivity. When they are used in the framing of building enclosure assemblies, attention must be given to mitigating energy losses due to thermal bridging of the steel members. In cold climates, such assemblies must include continuous insulation.

Building and Material Life-Cycle Impacts

- A Steel Recycling Institute EPD reports the following North American industry average cradle-to-gate impacts for one metric ton (2200 lb) of galvanized, cold-formed steel studs and track, manufactured by a mix of basic oxygen and electric arc furnace processes:

Nonrenewable primary energy consumption	29,000 MJ (28 million BTU)
Global warming potential	2300 kg (5000 lb) CO_2 eq.
Fresh water consumption	1100 L (290 gal)

Material and Production Attributes

- The postconsumer recycled content of light gauge steel framing members manufactured by the basic oxygen furnace process is approximately 20 percent, and of members manufactured by the electric arc furnace process, approximately 70 percent.

Nominal Gauge	Minimum Thickness of Steel Sheet	
	Loadbearing Members	Nonloadbearing Members
10	0.118" (3.00 mm)	
12	0.097" (2.45 mm)	
14	0.068" (1.72 mm)	0.068" (1.72 mm)
16	0.054" (1.37 mm)	0.054" (1.37 mm)
18	0.043" (1.09 mm)	0.043" (1.09 mm)
21	0.033" (0.84 mm)	0.033" (0.84 mm)
20		0.030" (0.75 mm)
22		0.024" (0.60 mm)
25		0.018" (0.45 mm)
28		0.015" (0.38 mm)

Figure 12.2
Minimum thicknesses of base sheet metal (not including the metallic coating) for light gauge steel framing members. Shaded figures indicate the most commonly used. Traditional *gauge* designations are also shown. Note that lower gauge numbers correspond to greater metal thickness. Though still used in common parlance, gauge numbers are no longer included in industry standard specifications due to a lack of consistency in their translation to actual thicknesses. Metal thickness is also sometimes expressed in mils, or thousandths of an inch. For example, 0.033 inch equals 33 mils.

and nonloadbearing members to ASTM C645.

Light gauge steel members are identified using a standard nomenclature, similar to that used with hot-rolled steel structural shapes, including member depth, a letter designation for shape, member width, and metal thickness. For example, a 600S162-54 member is a 6.00-inch-deep ("600") stud/joist section ("S"), 1.625 inches wide ("162"), made from 54-mil-thick sheet metal ("54"). Standard designations and the range of sizes available for common member types are listed in Figure 12.3.

Some manufacturers produce specially formed member types with improved structural properties. For example, the cross-sectional profile of a stud/joist section may be altered to enhance its strength and stiffness. Or, studs may be passed through rollers that produce a dense array of dimples in the formed metal. The additional cold working of the metal that occurs during this process and the patterning of the surface produce a stud with greater strength and stiffness without increasing metal thickness. In addition, a wide variety of angles, straps, plates, channels, and other shapes are used in the joining and bracing of members (Figure 12.4).

Like wood light members, light gauge steel shapes are furnished in standard lengths. They are cut to length on the construction job site with power saws or with special electric or hand shears, depending on their thickness. For large projects,

Cold-Formed Member	Example Designation	Available Depths	Available Widths
S: Stud/ Joist Section	600S162-54	1.625", 2.5", 3.5", 3.625", 4", 5.5", and 6"–16" *41, 64, 90, 92, 102, 140, and 152–406 mm*	1.25"–2.5" *32 mm–64 mm*
T: Track Section	362T125-30	Same as above	1.25"–2" *32 mm–51 mm*
U: Channel Section	250U050-54	0.75"–2.5" *19 mm–64 mm*	0.5" *13 mm*
F: Furring Channel	087F125-43	0.875"–1.25" *22 mm–32 mm*	1.25"–2.5" *32 mm–64 mm*

FIGURE 12.3
Standard light gauge steel shapes and sizes.

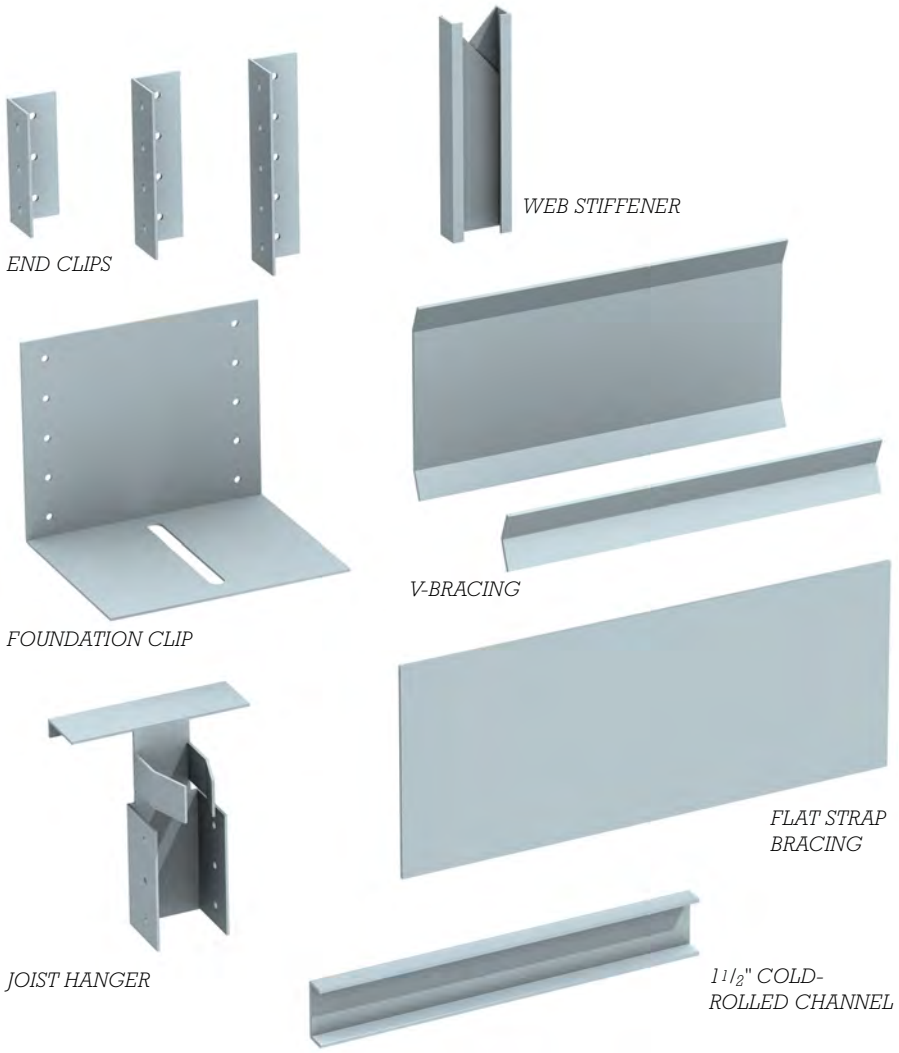


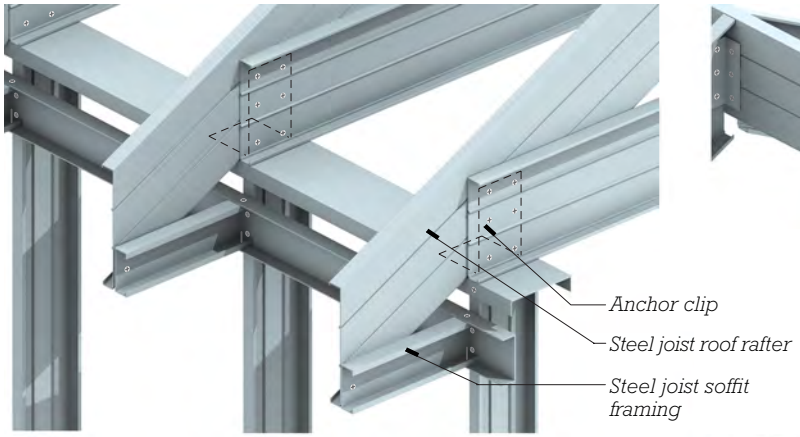
FIGURE 12.4
Standard accessories for light gauge steel framing. End clips are used to join members that meet at right angles. Foundation clips attach the ground-floor platform to anchor bolts embedded in the foundation. Joist hangers connect joists to headers and trimmers around openings. The web stiffener is a two-piece assembly that is inserted inside a joist and screwed to its vertical web to help transmit wall loads vertically through the joist. The remaining accessories are used for bracing.

members may be delivered precut to the required lengths.

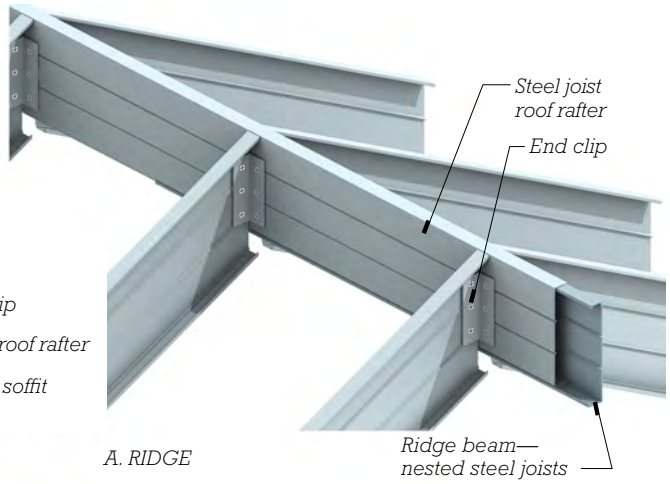
Light gauge steel members are usually joined with *self-drilling screws*, which drill their own holes and form helical threads in the holes as they are installed. Driven rapidly by hand-held electric or pneumatic tools, these screws are plated with cadmium or zinc to resist corrosion, and they are available in an assortment of diameters and lengths to suit a full range of connection needs. Welding is often employed to assemble panels of light gauge steel framing that are prefabricated in a factory, and is sometimes used on the building site where stronger connections are needed. Other fastening techniques include hand-held clinching devices that join members without screws or welds and pneumatically driven pins, analogous to nails in wood light frame construction, that penetrate the members and hold by friction.

Light Gauge Steel Framing

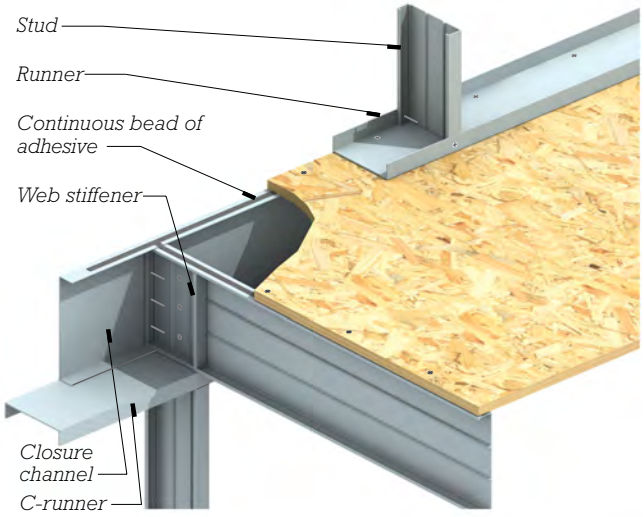
The sequence of construction for a building constructed with light gauge steel members is analogous to that described in Chapter 5 for wood light framing (Figures 12.5 through 12.12). Framing proceeds platform-fashion: The ground floor is framed with



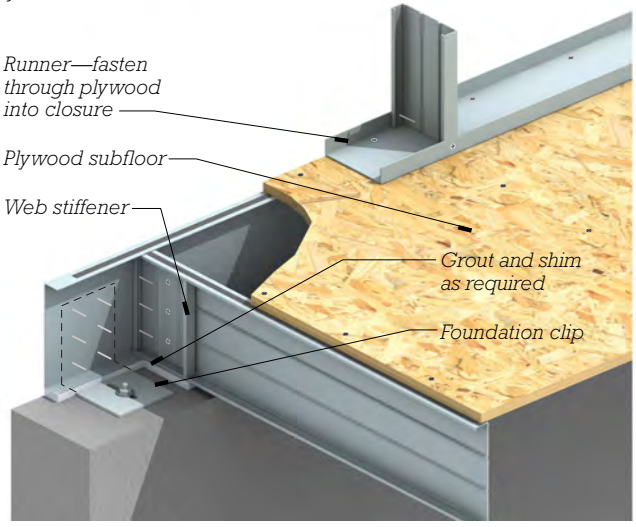
B. EAVE



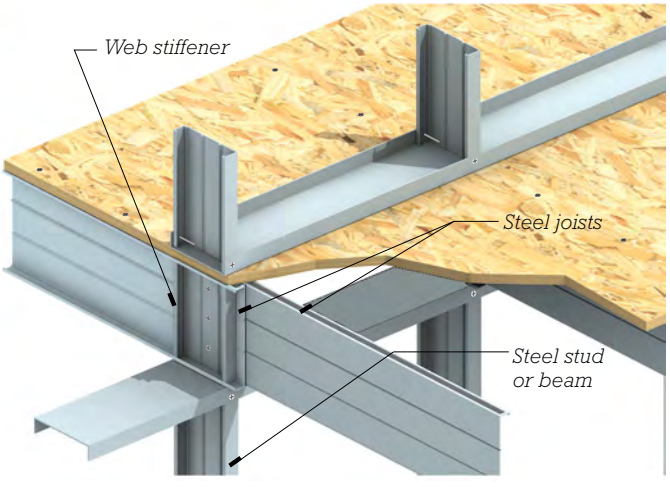
A. RIDGE



C. JOIST BEARING AT UPPER FLOOR



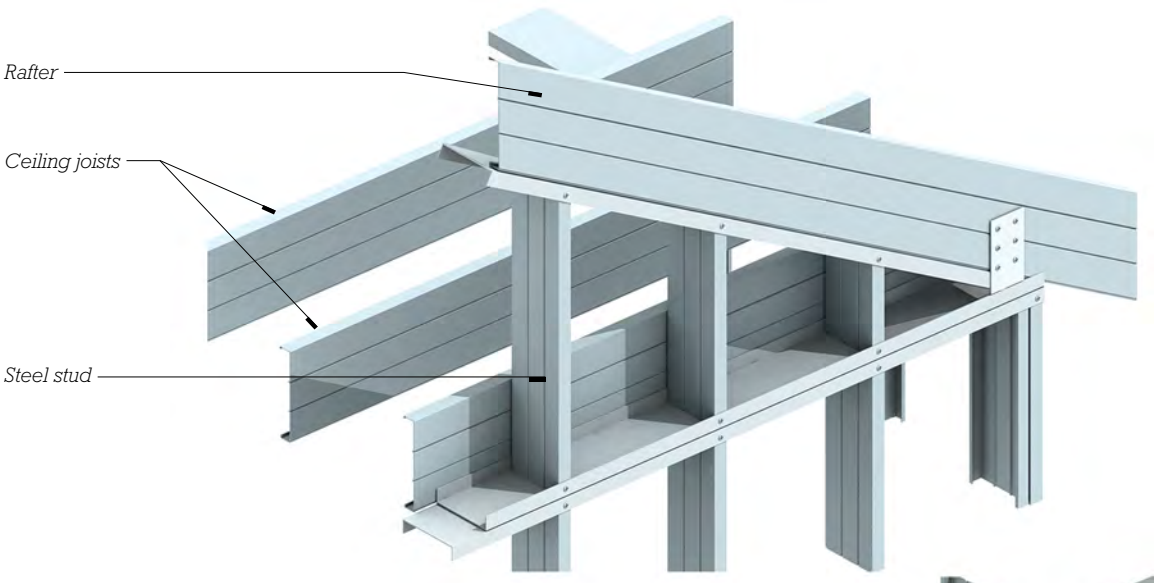
D. JOIST BEARING AT FOUNDATION



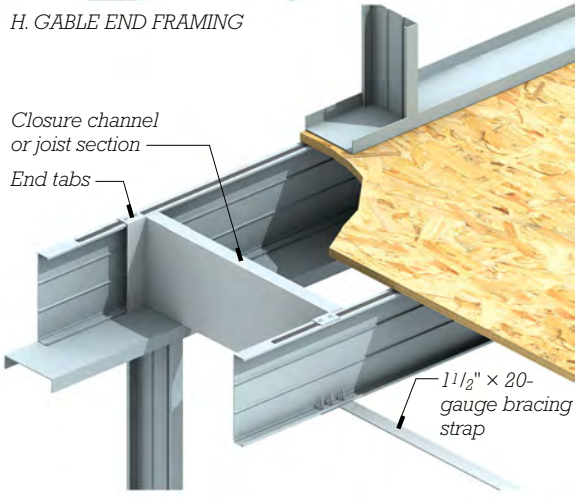
E. INTERIOR JOIST BEARING

FIGURE 12.5

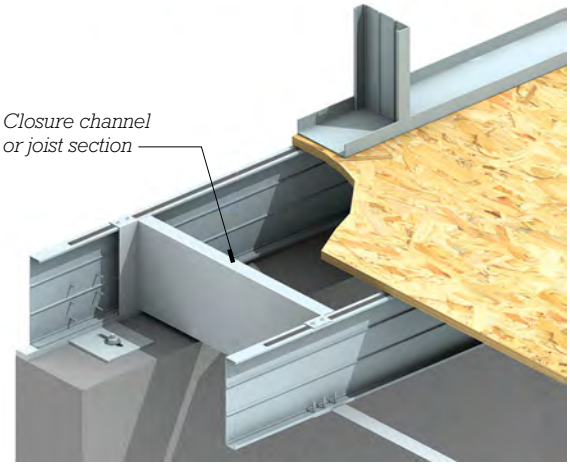
Typical light gauge framing details. Each detail is keyed by letter to a circle on the central whole-building diagram included as part of this figure, to show its location in the frame. (*A*) A pair of nested joists makes a boxlike ridge beam. (*B*) Anchor clips are sandwiched between the ceiling joists and rafters to hold the roof framing down to the wall. (*C*) A web stiffener helps transmit vertical forces from each stud through the end of the joist to the stud in the floor below. Mastic adhesive cushions the joint between the subfloor and the steel framing. (*D*) Foundation clips anchor the entire frame to the foundation. (*E*) At interior joist bearings, joists are overlapped back-to-back and a web stiffener is inserted. *(continued)*



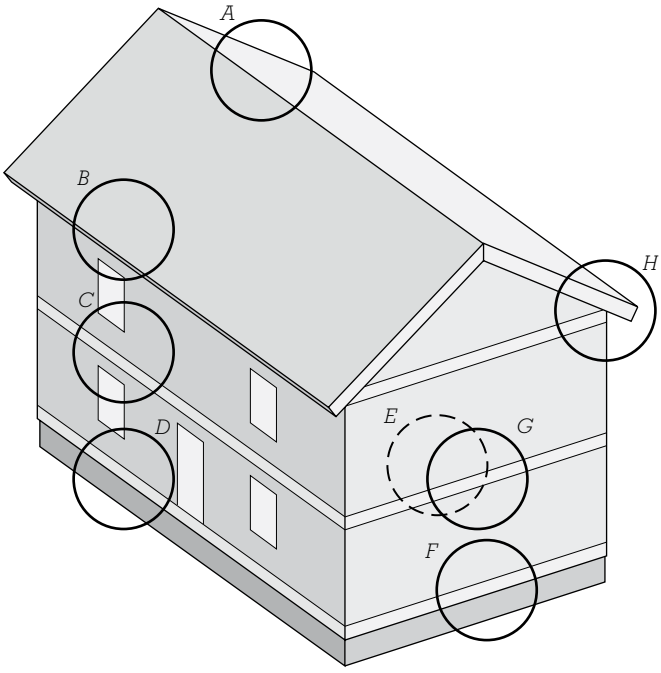
H. GABLE END FRAMING



G. JOIST PARALLEL TO END WALL



F. JOIST PARALLEL TO FOUNDATION



DETAIL KEY

FIGURE 12.5 ***continued***

(*F, G*) Short crosspieces brace the last joist at the end of the building and help transmit stud forces through to the wall below. (*H*) Like all these details, the gable end framing is directly analogous to the corresponding detail for a wood light frame building as shown in Chapter 5.

Interactive Exercise

stud/joists. Mastic adhesive is applied to the upper edges of the joists, and structural wood panels are laid down and screwed or pinned to the upper flanges of the joists. Next, stud/joists are laid out on the completed subfloor and assembled to make wall frames. These frames are sheathed, tilted up, attached to the subfloor, and braced. Upper-floor platforms and walls proceed, in sequence, in the same manner. Finally, the ceiling and roof are framed in much the same way. Prefabricated trusses of light gauge steel members that are screwed or welded together are often used to frame ceilings and roofs (Figures 12.13 and 12.14). It is possible, in fact, to frame any building with light gauge steel members that can be framed with nominal 2-inch (38-mm) wood members.

Openings in floors and walls are framed analogously to openings in wood light frame construction, with doubled members around each opening and headers over doors and windows (Figures 12.6, 12.7, and 12.10). Joist hangers and right-angle clips of sheet steel are used to join members around openings. Light gauge members are designed so that they can be *nested* to form a tubular configuration that is especially strong and stiff when used for a ridge board or header (Figures 12.5*A* and 12.6).

Because light gauge steel members are more prone than their wood counterparts to twisting or buckling under load, more attention must be paid to their bracing and bridging. The studs in tall walls are generally braced at 4-foot (1200-mm) intervals, either with steel straps screwed to the faces of the studs or with 1½-inch (38-mm) channels passed through the punched openings in the studs and welded or screwed to an angle clip at each stud (Figures 12.8 and 12.17). Floor joists are bridged with joist blocking between the joists or steel straps screwed to their top and bottom edges. In locations where large vertical forces must pass through floor joists (as occurs where loadbearing studs sit on the edge of a floor platform), steel *web stiffeners* are screwed to the thin webs of the joists to prevent them from buckling (Figure 12.5*C*, *D*, *E*). Lateral bracing for walls consists of diagonal steel straps screwed to the studs (Figure 12.8). Subflooring, wall sheathing, roof sheathing, and interior finish materials also all contribute significantly to resistance to buckling, twisting, and lateral wind and earthquake loads.

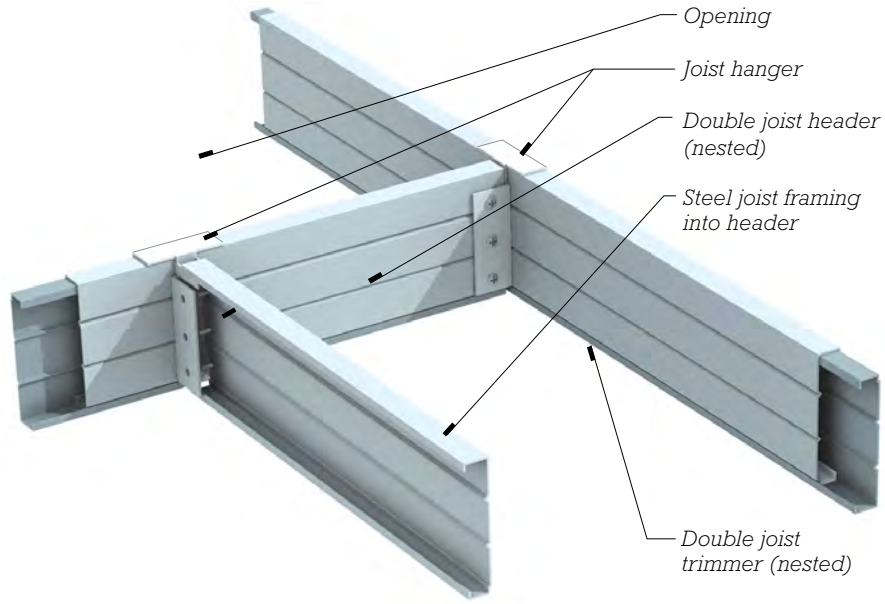


FIGURE 12.6
Headers and trimmers for floor openings are doubled and nested to create a strong, stable box member. Only one vertical flange of the joist hanger is attached to the joist; the other flange would be used instead if the web of the joist were oriented to the left rather than the right.

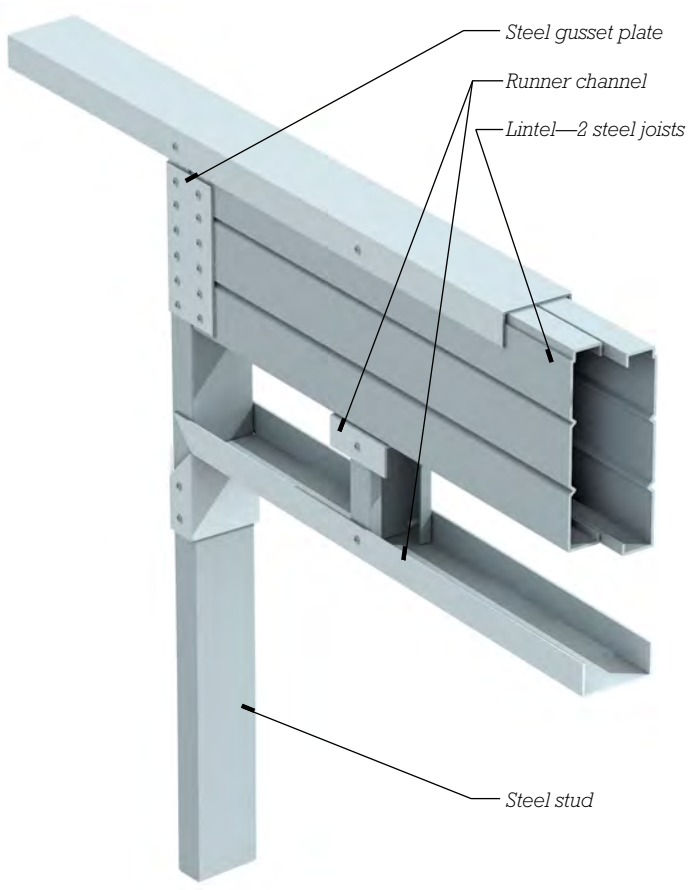


FIGURE 12.7
A typical window or door head detail. The header is made of two joists placed with their open sides together. The top plate of the wall, which is a runner channel, continues over the top of the header. Another runner channel is cut and folded at each end to frame the top of the opening. Short studs are inserted between this channel and the header to maintain the rhythm of the studs in the wall.

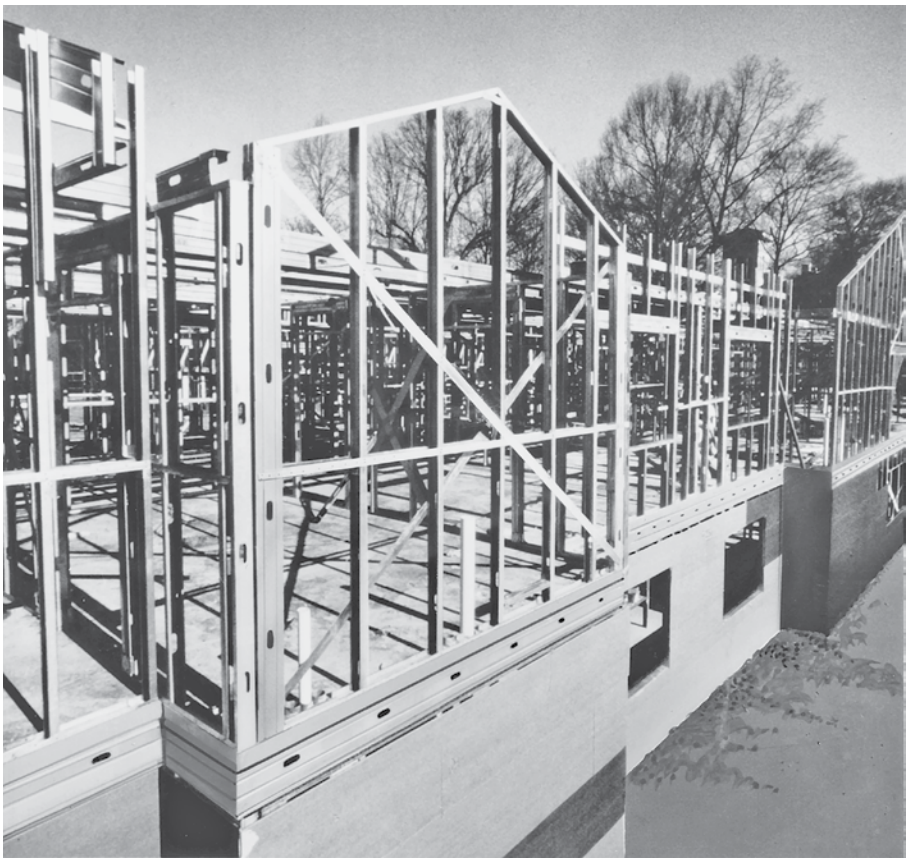


FIGURE 12.8
Diagonal strap braces stabilize upper-floor wall framing for an apartment building. A special tool is used to draw the metal strapping tight as it is installed. The studs are also braced against buckling with horizontal strapping across both faces of the studs at approximately their mid-height. *(Courtesy of United States Gypsum Company.)*

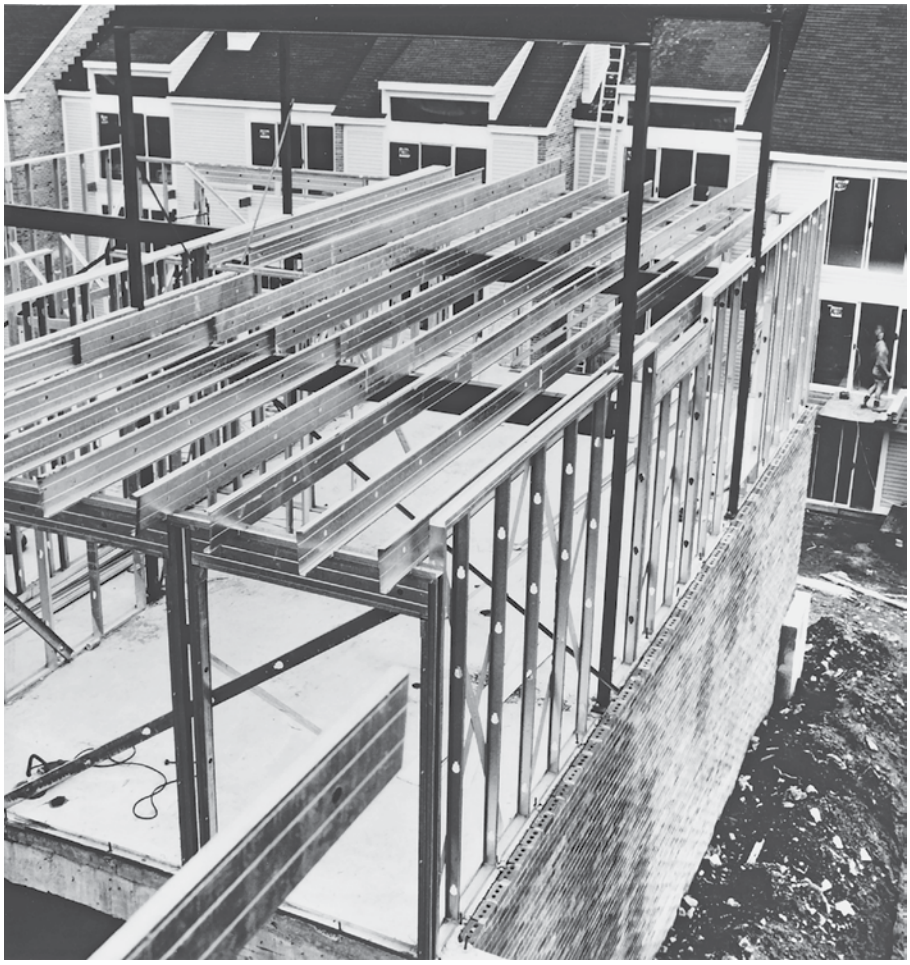


FIGURE 12.9
Ceiling joists in place for an apartment building. A brick veneer cladding has already been added to the ground floor. *(Courtesy of United States Gypsum Company.)*

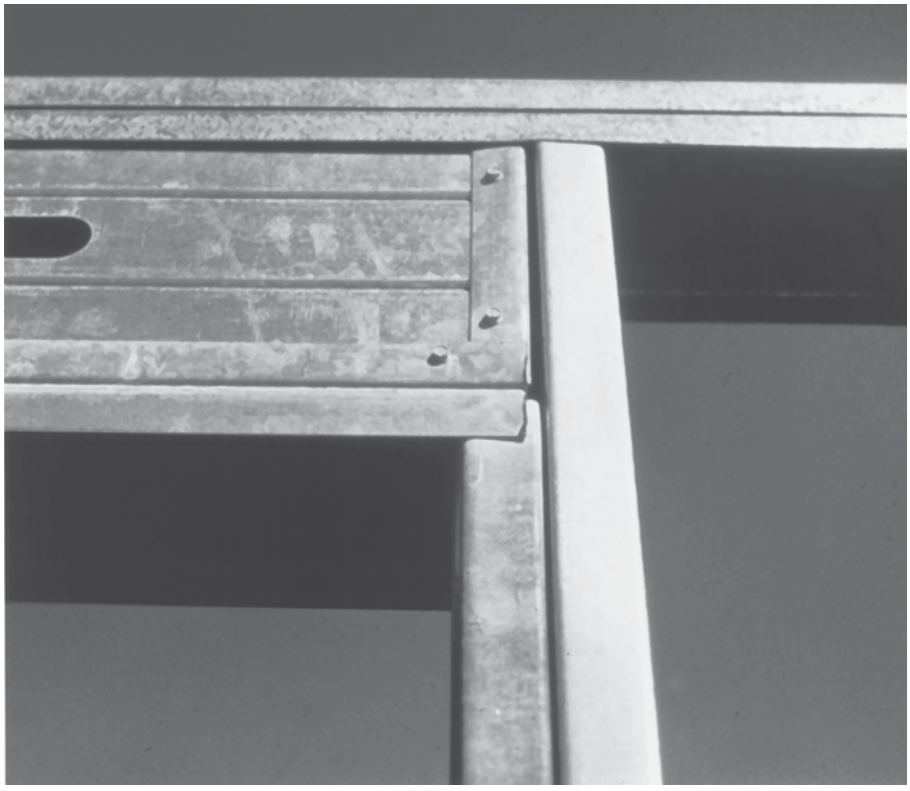


FIGURE 12.10
Close-up view of a window header connection. Because a supporting stud has been inserted under the end of the header, a large gusset plate such as the one shown in Figure 12.7 is not required. *(Courtesy of Unimast Incorporated, www.unimast.com.)*

FIGURE 12.11
Flexible metal conduit runs through prepunched openings in metal wall studs. The junction box is supported on metal bracket spanning between studs. *(Photo by Joseph Iano.)*

Where a light gauge steel frame building is constructed to be fully noncombustible, wood structural panels cannot be used for subfloors or wall sheathing. Instead, floors may be constructed of corrugated steel decking with concrete topping or precast concrete. Exterior walls are sheathed with *gypsum sheathing panels*, which are similar to gypsum wallboard but made more resistant to moisture and weather with glass mat faces and specially formulated water-resistant gypsum cores (Figure 12.16).

FIGURE 12.12
A detail of eave framing. *(Courtesy of Unimast Incorporated, www.unimast.com.)*

FIGURE 12.13
A worker tightens the last screws to complete a connection in a light gauge steel roof truss. The truss members are held in alignment during assembly by a simple jig made of plywood and blocks of framing lumber. *(Courtesy of Unimast Incorporated, www.unimast.com.)*

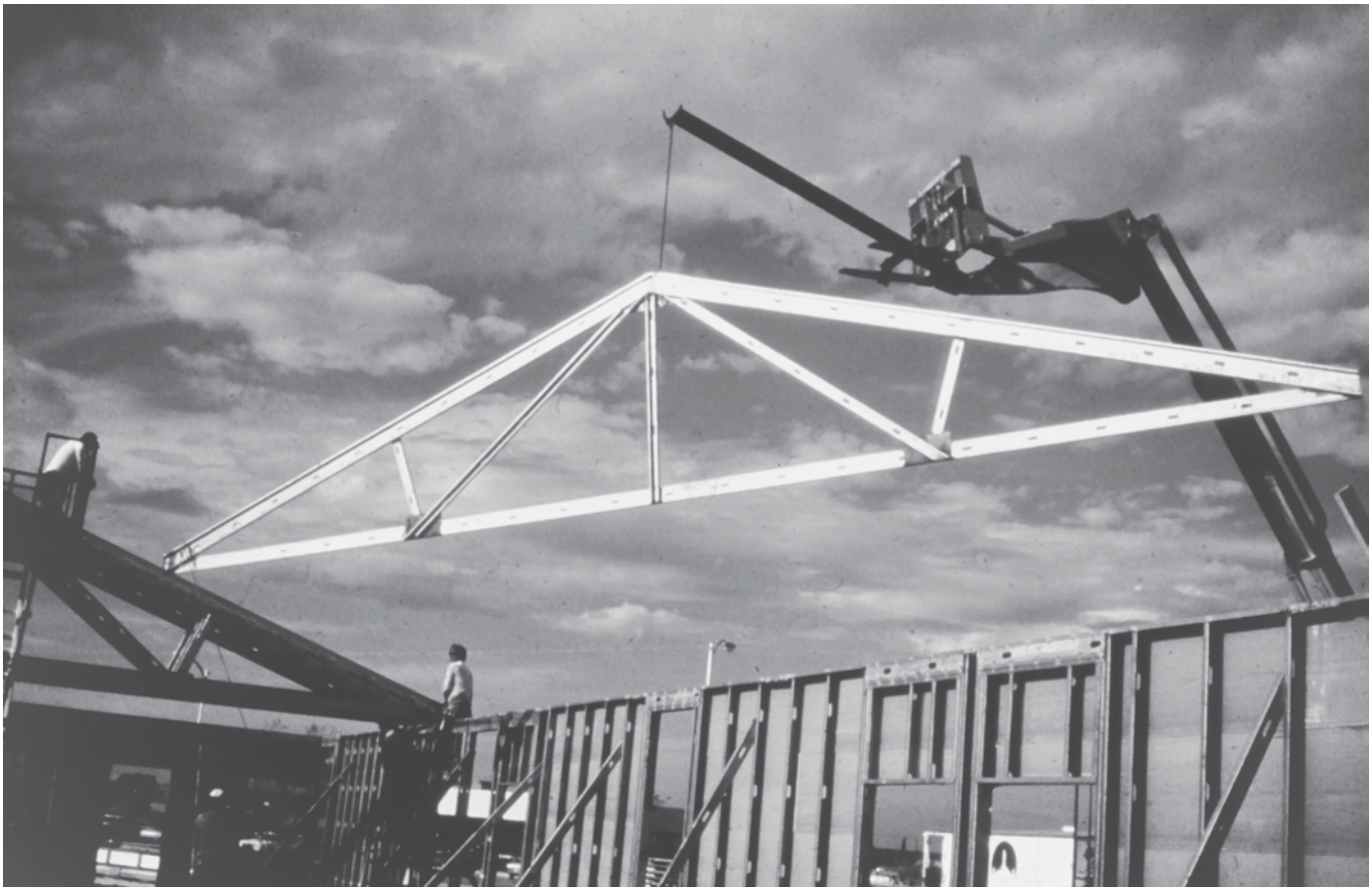


Figure 12.14
Installing steel roof trusses. *(Courtesy of Unimast Incorporated, www.unimast.com.)*

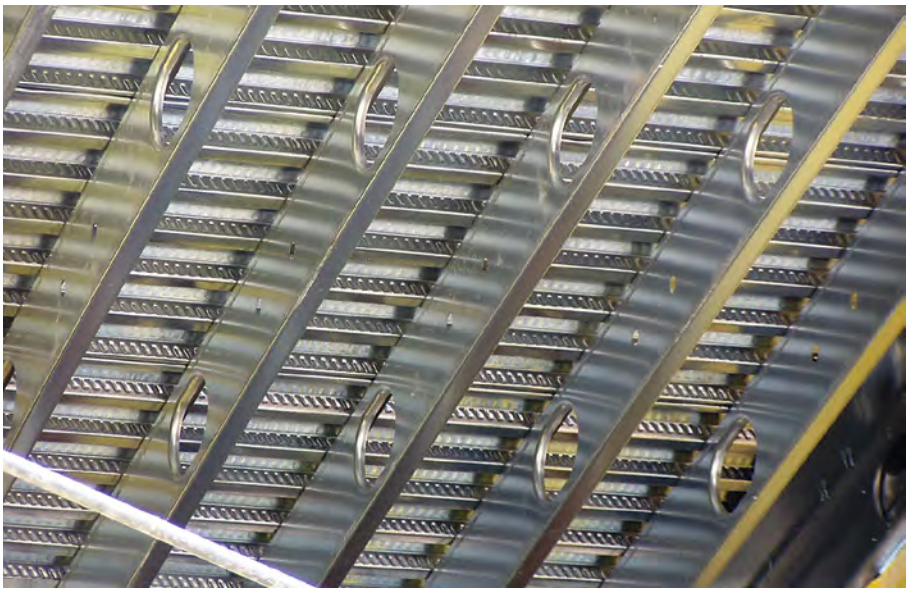


Figure 12.15
Light gauge steel joists supporting corrugated composite metal decking. Note the preformed openings in the joists, for easy routing of piping and other services within the depth of the framing. *(Photo by Joseph Iano.)*

FIGURE 12.16
Gypsum sheathing panels being applied over metal stud framing on a residential noncombustible building. *(Photo by Joseph Iano.)*

OTHER USES OF LIGHT GAUGE STEEL FRAMING

Light gauge steel members are used to construct many components of fire-resistant buildings whose primary structures are made of structural steel, concrete, or masonry. These components include interior walls and partitions (Chapters 23); suspended ceilings (Chapter 24); and fascias, parapets, and backup walls for many kinds of exterior cladding materials (Chapters 19 and 20; Figures 12.17, 12.18). In construction documents, light gauge steel members used for framing interior partitions and other nonloadbearing applications are specified as *nonstructural metal framing*, as distinct from cold-formed metal framing, the latter term being reserved for light gauge steel members used in structural applications and exterior wall cladding systems (even though both types of members are, in fact, cold-formed). The different specifications reflect the different requirements to which these two types of framing must be designed and constructed.

Light gauge steel studs can be combined with concrete to produce thin, but relatively stiff, wall panel systems. Both loadbearing and nonloadbearing panels can be made that are suitable for use in residential and light commercial buildings. A variety of production methods are possible that involve casting an approximately 2-inch (50-mm)-thick concrete facing onto a framework of steel studs. The concrete may be sitecast on the building site or precast in a factory. The concrete-to-steel bond may be created by stud anchors, sheet metal shear strips, welded wire reinforcing, or expanded metal that is welded or screwed to the studs and then becomes embedded in the concrete. In loadbearing applications, the concrete panels provide shear resistance while the steel studs provide most of the resistance to gravity and wind loads acting perpendicular to the face of the panel.

FIGURE 12.17
Light gauge steel stud infill between concrete and structural steel will support the exterior cladding. Note the horizontal rows of steel strap bracing.
(Photo by Joseph Iano.)

FIGURE 12.18
Light gauge steel stud framing forms the exterior enclosure for this building structured with posttensioned concrete.
(Photo by Joseph Iano.)

Preliminary Design of Light Gauge Steel Frame Structures

- Estimate the depth of rafters on the basis of the horizontal (not slope) distance from the outside wall of the building to the ridge board in a gable or hip roof and the horizontal distance between supports in a shed roof. Estimate the depth of a rafter at 1/24 of this span, rounded up to the nearest 2-inch (50-mm) dimension.
- The depth of light gauge steel **roof trusses** is usually based on the desired roof pitch. A typical depth is one-quarter of the width of the building, which corresponds to a 6:12 pitch.
- Estimate the depth of light gauge steel **floor joists** as 1/20 of the span, rounded up to the nearest 2-inch (50-mm) dimension.
- For **loadbearing studs**, add up the total width of floor and roof slabs that contribute load to the stud wall. A 3⅝-inch (92-mm) or 4-inch (102-mm) stud wall can support a combined width of approximately 60 feet (18 m), and a 6-inch (152-mm) or 8-inch (203-mm) stud wall can support a combined width of approximately 150 feet (45 m).
- For **exterior cladding backup walls**, estimate that a 3⅝-inch (92-mm) stud may be used to a maximum height of 12 feet (3.7 m), a 6-inch (150-mm) stud to 19 feet (5.8 m), and an 8-inch (100-mm) stud to 30 feet (9.1 m). For brittle cladding materials such as brick masonry, select a stud that is 2 inches (50 mm) deeper than these numbers would indicate.

All framing members are usually spaced at 24 inches (600 mm) o.c.

These approximations are valid only for purposes of preliminary building layout and must not be used to select final member sizes. They apply to the normal range of building occupancies, such as residential, office, commercial, and institutional buildings.

For manufacturing and storage buildings, use somewhat larger members. For more comprehensive information on preliminary selection and layout of structural members, see Edward Allen and Joseph Iano, *The Architect's Studio Companion* (6th ed.), Hoboken, NJ, John Wiley & Sons, 2017.

In situations where noncombustibility is not a requirement, metal and wood light framing may be mixed in the same building. Some builders find it economical to use wood to frame exterior walls, floors, and roof, with steel framing for interior partitions. Sometimes all walls, interior and exterior, are framed with steel, and floors are framed with wood. Steel trusses made of light gauge members may be applied over wood frame walls. In such mixed uses, special care must be taken in the details to ensure that wood shrinkage will not create unforeseen stresses or damage to finish materials. Steel framing also may be used in lieu of wood where the risk of damage from termites is high.

Insulating Light Gauge Steel Frame Structures

The thermal conductivity of light gauge steel framing members is much higher than that of wood, and almost any other primary structural material as well. In cold regions, light gauge steel framing must be detailed and insulated to minimize *thermal bridging* through the steel members. Without such measures, the thermal performance of the wall or roof is greatly reduced, energy losses increase, and moisture condensation within the framing cavity or on interior building surfaces may occur, with attendant corrosion or decay, growth of mold and mildew, and discoloration of finishes.

As a first step, a layer of *continuous insulation*, consisting of rigid plastic foam, semirigid mineral fiber, or other insulation type, must be placed on one side or the other of framing members. The minimum amount of such insulation varies, with colder climates requiring greater insulation values than warmer ones (Figure 16.12). The preferred location for continuous insulation is on the exterior (cold) side of the metal components, which keeps metal components warmer and does a better job of isolating point of potential thermal bridging. Placing continuous insulation on the interior, warm side of the framing exposes the metal components to lower temperatures,

increasing the risk of condensation within the framing cavity. (For a more in-depth discussion of the role of exterior insulation in building enclosure assemblies, see Chapter 16.)

Additionally, where steel members may extend from inside to outside the building enclosure, such as at the roof eave of a simple house frame (Figures 12.5*B* and 12.12), steel members must be broken, insulating spacers must be inserted between inside and outside steel, or some other method must be used to minimize thermal bridging at such locations.

Finishes for Light Gauge Steel Framing

Any exterior or interior finish material that is used in wood light frame construction may be applied to light gauge steel frame construction. Whereas finish materials are often fastened to a wood frame with nails, screws are used with a steel frame. Wood trim components are applied with special finish screws, analogous to finish nails, which have very small heads.

Advantages and Disadvantages of Light Gauge Steel Framing

Light gauge steel framing shares most of the advantages of wood light framing: It is versatile and flexible; requires only simple, inexpensive tools; furnishes internal cavities for building services and thermal insulation; and accepts an extremely wide range of exterior and interior finish materials. Additionally, steel framing may be used in buildings for which noncombustible construction is required by the building code, thus extending its use to larger buildings and those whose uses require a higher degree of resistance to fire.

Steel framing members are significantly lighter in weight than the wood members to which they are structurally equivalent, an advantage that is often enhanced by spacing steel studs, joists, and rafters at 24 inches (600 mm) o.c. rather than 16 inches (400 mm) o.c. Light gauge steel joists and rafters can span slightly longer distances than nominal 2-inch (50-mm) wood members of the same depth. Steel members tend to be straighter and more uniform than wood members (Figure 12.19), and they are much more stable dimensionally because they are unaffected by changing humidity. Although they may corrode if exposed to moisture over an extended period of time, steel framing members cannot fall victim to termites or decay.

Compared to walls and partitions of masonry construction, equivalent walls and partitions framed with steel studs are much lighter in weight, easier to insulate, and accept electrical wiring and pipes for plumbing and heating much more readily. Steel framing, because it is a dry process, may be carried out during wet or cold weather conditions that would make masonry construction difficult. Masonry walls tend to be much stiffer and more resistant to the passage of sound than steel-framed walls, however.

Light Gauge Steel Framing and the Building Codes

Light gauge steel framing members are noncombustible and can be used in any building code construction type as long as they meet necessary fire resistance rating requirements (Figure 1.5). When unprotected, light gauge steel framing members will lose their strength and stiffness rapidly when exposed to the heat of fire. However, with suitable protection, such as gypsum board or plaster, loadbearing light gauge steel assemblies can readily meet 2-hour fire resistance rating requirements. This makes them suitable as a structural loadbearing system for any construction type except Type I-A, enabling their use in a wide range of building types and sizes.

In its International Residential Code (IRC) for One- and Two-Family Dwellings, the International Code Council has incorporated prescriptive requirements for steel-framed residential construction. In many cases, these requirements, with their structural tables and standard details, allow builders to design and construct light gauge steel-framed houses without having to employ an engineer or architect, just as they are able to do with wood light frame construction.

FIGURE 12.19
The straightness of steel studs is apparent in these tall stud walls enclosing a building framed with structural steel. *(Courtesy of Unimast Incorporated, www.unimast.com.)*

Metals in Architecture

Metals are dense, lustrous materials that are highly conductive of heat and electricity. They are generally *ductile*, meaning that they can be hammered thin or drawn into wires. They can be liquefied by heating and will resolidify as they cool. Most metals corrode by oxidation. Metals include the strongest building materials presently in common use, although stronger materials based on carbon or aramid fibers are beginning to appear more frequently in building construction applications.

Metals are usually found in nature in the form of oxide ores. These ores are refined by processes that involve heat and reactant materials or, in the case of aluminum, electrolysis.

In the building construction industry, metals may be classified broadly as either ferrous, meaning that they consist primarily of iron, or nonferrous, that is, all other metals. Because iron ore is an abundant mineral and is relatively easy to refine, ferrous metals tend to be much less expensive than nonferrous ones. The ferrous metals are also the strongest, but most have a tendency to rust. Nonferrous metals in general are considerably more expensive on a volumetric basis than ferrous metals, but unlike ferrous metals, most of them form thin, tenacious oxide layers that protect from further corrosion under normal atmospheric conditions. This makes many of the nonferrous metals valuable for finish components of buildings. Many of the nonferrous metals are also easy to work and attractive to the eye.

Modifying the Properties of Metals

A metal is seldom used in its chemically pure state. Instead, it is mixed with other elements, primarily other metals, to modify its properties for a particular purpose. Such mixtures are called *alloys*. An alloy that combines copper with a small amount of tin is known as bronze. A very small, closely controlled amount of carbon mixed with iron makes steel. In both of these examples, the alloy is stronger and harder than the elemental metal that is its primary ingredient. Various alloys of iron (different steel alloys, to be more specific) are discussed in Chapter 11. Some of these have higher strengths, and some form self-protecting oxide layers because of the influence of the alloying elements they contain. Similarly, there are many alloys that consist primarily of aluminum; some are soft and easy to form, others are very hard and springy, still others are very strong, and so on.

The properties of many metals can also be changed by *heat treatment*. Steel that is *quenched*, that is, heated red-hot and then plunged in cold water, becomes much harder but brittle. Steel can be *tempered* by heating it to a moderate degree and cooling it more slowly, making it both hard and strong. Steel that is brought to a very high temperature and then cooled very slowly, a process called *annealing*, will become softer, easier to work, and less brittle. Many aluminum alloys can also be heat-treated to modify their characteristics.

Cold working is another way of changing the properties of a metal. When steel is beaten or rolled thinner at room temperature, its crystalline structure is altered in a way that makes it much stronger, though also somewhat more brittle. The highest-strength metals used in construction are steel wires and cables used to prestress concrete. Their high strength (about four times that of normal structural steel) is the result of drawing the metal through smaller and smaller orifices to produce the wire, a process that subjects the metal to a high degree of cold working. Cold-rolled steel shapes with substantially higher strengths than hot-rolled structural steel are used as reinforcing and as components of open-web joists. The effects of cold working are easily reversed by annealing. Hot rolling, which is, in effect, a self-annealing process, does not increase the strength of metal.

To change the appearance of metal or to protect it from oxidation, it can be coated with a thin layer of another metal. Steel is often *galvanized* by coating it with zinc to protect against corrosion, as described later in this sidebar. *Electroplating* is widely used to coat metals such as chromium and cadmium onto steel to improve the appearance of the steel and protect it from oxidation. An electrolytic process is used to *anodize* aluminum, adding a thin oxide layer of controlled color and consistency to the surface of the metal. To protect them and enhance their appearance, metals are frequently finished with nonmetallic coatings such as paints, lacquers, organic coatings, porcelain enamel, and thermosetting powders.

Fabricating Metals

Metals can be shaped in many different ways. *Casting* is the process of pouring molten metal into a shaped mold; the metal retains the shape of the mold as it cools. *Rolling*, which may be done either hot or cold, forms the metal by squeezing it between a series of shaped rollers. *Extrusion* is the process of squeezing heated, but not molten, metal through a shaped die to produce a long metal piece with a shaped profile matching the cutout in the die. *Forging* involves heating a piece of metal until it becomes soft, then beating it into shape. Forging was originally done by hand with a blacksmith's forge, hammer, and anvil. Now most forging is done with powerful hydraulic machinery that

forces the metal into shaped dies. *Stamping* is the process of squeezing sheet metal between two matching dies to give it a desired shape or texture. *Drawing* produces wires by pulling a metal rod through a series of progressively smaller orifices in hardened steel plates until the desired diameter is reached. These forming processes have varying effects on the strength of the resulting material: Cold drawing and cold rolling will harden and strengthen many metals. Forging imparts a grain orientation to the metal that closely follows the shape of the piece for improved structural performance. Casting tends to produce somewhat weaker metal than most other forming processes, but it is useful for making elaborate shapes (such as lavatory faucets) that could not be manufactured economically in any other way. Recent developments in steel casting enable the production of castings that are as strong as rolled steel shapes.

Metals can also be shaped by *machining*, which is a process of cutting unwanted material from a piece of metal to produce the desired shape. Among the most common machining operations is *milling*, in which a rotating cutting wheel is used to cut metal from a workpiece. To produce cylindrical shapes, a piece of metal is rotated against a stationary cutting tool in a *lathe*. Holes are produced by *drilling*, which is usually carried out either in a *drill press* or a lathe. Screw threads may be produced in a hole by the use of a helical cutting tool called a *tap*, and the external threads on a steel rod are cut with a *die*. (The threads on mass-produced screws and bolts are formed at high speed by special rolling machines.) Grinding and polishing machines are used to create and finish flat surfaces. Sawing, shearing, and punching operations, described in Chapter 11, are also common methods of shaping metal components.

An economical method of cutting steel of almost any thickness is with a *flame-cutting torch* that combines a slender, high-temperature gas flame with a jet of pure oxygen to burn away the metal. *Plasma cutting* with a tiny supersonic jet of superheated gas that blows away the metal can give more precise cuts at thicknesses of up to 2 inches (50 mm), and *laser cutting* gives high-quality results in thin metal plates.

Sheet metal is fabricated with its own particular set of tools. Shears are used to cut metal sheets. Folds are made on large machines called *brakes* (the results of which are called *brake metal*).

Joining Metal Components

Metal components may be joined either mechanically or by fusion. Most mechanical fastenings require drilled or punched holes for the insertion of screws, bolts, pins, or rivets. Some small-diameter screws that are used with thin metal components are shaped and hardened so that they are capable of drilling and tapping as they are driven. Many sheet metal components, especially roofing sheet and ductwork, are joined primarily with interlocking, folded connections.

High-temperature fusion connections are made by *welding*, in which a gas flame or electric arc melts the metal on both sides of the joint and allows it to flow together with additional molten metal from a welding rod or consumable electrode. *Brazing* and *soldering* are lower-temperature processes in which the parent metal is not melted. Instead, a different metal with a lower melting point (bronze or brass in the case of brazing and a tin alloy in the case of soldering) is melted into the joint and bonds to the pieces that it joins. A fully welded connection is generally as strong as the pieces it connects. A soldered connection is not as strong, but it is easy to make and works well for connecting copper plumbing pipes and sheet metal roofing. As an alternative to welding or soldering, adhesives are occasionally used to join metals in certain nonstructural applications.

Common Metals Used in Building Construction

The ferrous metals include cast iron, wrought iron, steel, and stainless steel. **Cast iron** contains relatively large amounts of carbon and impurities. It is the most *brittle* (vulnerable to sudden failure) ferrous metal. **Wrought iron** is produced by hammering semi-molten iron to produce a metal with long fibers of iron interleaved with long fibers of slag. It has very low iron content, making it stronger in tension and much less brittle than cast iron. Both cast iron and wrought iron found significant use in early metal structures. With the introduction of economical steelmaking processes, though, the roles of both of these earlier metals were largely taken over by steel. Even the ornamental metalwork that we refer to today as wrought iron is frequently made of mild steel. **Steel** is discussed in some detail in Chapter 11, and its many uses are noted throughout this book. In general, all these ferrous metals are very strong, relatively inexpensive, easy to form and machine, and must be protected from corrosion.

Stainless steel, made by alloying steel with other metals, primarily chromium and nickel, forms a self-protecting oxide coating that makes it highly resistant to corrosion. It is harder to form and machine than mild steel and is more costly. It is available in attractive finishes that range from matte textures to a mirror polish. Stainless steel is frequently used in the manufacture of fasteners, roofing and flashing sheet, hardware, railings, and other ornamental metal items.

Metals in Architecture (continued)

Stainless steel is available in different alloys distinguished, most importantly, by their level of corrosion resistance. *Type 304 stainless steel* is the type most commonly specified and provides adequate corrosion resistance for most applications. Type 304 stainless steel may also be referred to as Type 18-8, where the two numbers refer to the percentages of chromium and nickel, respectively, in this alloy. *Type 316 stainless steel*, with higher nickel content and the addition of small amounts of molybdenum, is more corrosion-resistant than Type 304. It is specified for use in marine environments where salt-laden air can lead to the accelerated corrosion of less resistant stainless steel alloys. *Type 410 stainless steel* has a lower chromium content and is less corrosion-resistant than the 300 series alloys. However, this alloy also has a different metallic crystal structure that, unlike the 300 series alloys, allows it to be hardened through heat treatment. Self-drilling, self-tapping stainless steel fasteners, whose threads must be tough enough to cut through structural steel or concrete, are frequently made of hardened Type 410 stainless steel.

Aluminum (spelled and pronounced "aluminium" in the British Commonwealth) is the nonferrous metal most often used in construction. Its density is about one-third that of steel, and it has moderate to high strength and stiffness, depending on which of a multitude of alloys is selected. It can be hardened by cold working, and some alloys can be heat-treated for increased strength. It can be hot- or cold-rolled, cast, forged, drawn, and stamped, and is particularly well adapted to extrusion. Aluminum is self-protecting from corrosion, easy to machine, and has thermal and electrical conductivities that are almost as high as those of copper. It is easily made into thin foils that find wide use in thermal-insulating and vapor-retarding materials. With a mirror-finish, aluminum in foil or sheet form reflects more heat and light than any other architectural material. Typical uses of aluminum in buildings include roofing and flashing sheet, ductwork, curtain wall components, window and door frames, grills, ornamental railings, siding, hardware, electrical wiring, and protective coatings for other metals, chiefly steel. Aluminum powder is used in metallic paints, and aluminum oxide is used as an abrasive in sandpaper and grinding wheels. For more information about aluminum alloys and the extrusion process, see Chapter 21.

Copper and copper alloys are widely used in construction. Copper is slightly more dense than steel and is bright orange-red in color. When it oxidizes, it forms a self-protecting coating that ranges in color from blue-green to black, depending on the contaminants in the local atmosphere. Copper is moderately strong and can be made stronger by alloying or cold working, but it is not amenable to heat treatment. It is ductile and easy to fabricate. It has the highest thermal and electrical conductivity of any metal used in construction. It may be formed by casting, drawing, extrusion, and hot- or cold-rolling. The primary uses of copper in buildings are roofing and flashing sheet, piping and tubing, and wiring for electricity and communications. Copper is an alloying element in certain corrosion-resistant steels, and copper salts are used as wood preservatives.

Copper is the primary constituent of two versatile alloys, bronze and brass. **Bronze** is a reddish-gold metal that traditionally consists of 90 percent copper and 10 percent tin. Today, however, the term "bronze" is applied to a wide range of alloys that may also incorporate such metals as aluminum, silicon, manganese, nickel, and zinc. These various bronzes are found in buildings in the form of statuary, bells, ornamental metalwork, door and cabinet hardware, and weatherstripping. **Brass** is formulated of copper and zinc plus small amounts of other metals. It is usually lighter in color than bronze, more of a straw yellow, but in contemporary usage the line between brasses and bronzes has become rather indistinct, and the various brasses occur in a wide range of colors, depending on the formulation. Brass, like bronze, is resistant to corrosion. It can be polished to a high luster. It is widely used in hinges and doorknobs, weatherstripping, ornamental metalwork, screws, bolts, nuts, and plumbing faucets (where it is usually plated with chromium). On a volumetric basis, brass, bronze, and copper are expensive metals, but they are often the most economical materials for applications that require their unique combination of functional and visual properties. For greater economy, they are frequently plated electrolytically onto steel for such uses as door hinges and locksets.

Zinc is a blue-white metal that is low in strength, relatively brittle, and moderately hard. Zinc sheet is used for roofing and flashing. Alloys of zinc are used for casting small hardware parts such as doorknobs, cabinet pulls and hinges, bathroom accessories, and components of electrical fixtures. These *die castings*, which are usually electroplated with another metal such as chromium for appearance, are not especially strong, but they are economical and they can be very finely detailed.

The most important use of zinc in construction is for galvanizing, the application of a zinc coating to prevent steel from rusting. The zinc itself forms a self-protecting gray oxide coating, and even if the zinc is accidentally scratched through to the steel beneath, the zinc interacts electrochemically with the exposed steel to continue to

protect the steel from corrosion—a phenomenon called *galvanic protection*. *Hot-dip galvanizing*, in which the steel parts are submerged in a molten zinc bath to produce a thick coating, is the most durable form of galvanizing. Much less durable is the thin coating produced by *electrogalvanizing*. Threaded steel fasteners and other small parts may be *mechanically galvanized*, in which zinc is fused to the steel at room temperature in a tumbler that contains zinc dust, impact media (such as ball bearings, for example), and other materials. Mechanical galvanizing produces a coating that is especially uniform and consistent in thickness. Steel sheet for architectural roofing is also frequently coated with an aluminum-zinc alloy coating. The aluminum provides a superior protective oxide coating, and the zinc provides galvanic protection if the coating becomes damaged and the base steel exposed. (For a more detailed discussion of galvanic action, see Chapter 17.)

Tin is a soft, ductile, silvery metal that forms a self-protecting oxide layer. The ubiquitous tin can is actually made of sheet steel with an internal corrosion-resistant coating of tin. Tin is found in buildings primarily as a constituent of terne metal, an alloy of 80 percent lead and 20 percent tin that was used in the past as a corrosion-resistant coating for steel or stainless steel roofing sheet. Today, zinc-tin alloy coated steel and stainless steel sheets are available for use as roofing metals that are close in appearance and durability to traditional terne metal.

Chromium is a very hard metal that can be polished to a brilliant mirror-finish. It does not corrode in air. It is often electroplated onto other metals for use in ornamental metalwork, bathroom and kitchen accessories, door hardware, and plumbing and lighting fixtures. It is also a major alloying ingredient in stainless steel and many other metals, to which it imparts hardness, strength, and corrosion resistance. Chromium compounds are used as colored pigments in paints and ceramic glazes.

Magnesium is a strong, remarkably lightweight metal (less than one-quarter the density of steel) that is much used in aircraft but remains too costly for general use in buildings. It is found on the construction site as a material for various lightweight tools and as an alloying element that increases the strength and corrosion resistance of aluminum.

Titanium is also low in density, about half the weight of steel, very strong, and one of the most corrosion-resistant of all metals. It is a constituent in many alloys, and its oxide has replaced lead oxide in paint pigments. Though expensive, titanium has recently begun to appear on the building construction site in the form of architectural sheet metal for siding and roofing.

MasterFormat Sections for Light Gauge Steel Frame Construction

05 40 00	**COLD-FORMED METAL FRAMING**
05 41 00	**STRUCTURAL METAL STUD FRAMING**
05 42 00	**COLD-FORMED METAL JOIST FRAMING**
05 44 00	**COLD-FORMED METAL TRUSSES**
09 22 00	**SUPPORT FOR PLASTER AND GYPSUM BOARD**
09 22 16	Non-Structural Metal Framing

Key Terms

light gauge steel
cold-formed metal framing
stud/joist section
track section
channel section
furring channel
gauge
self-drilling screw
nested member
web stiffener
gypsum sheathing panel
nonstructural metal framing
thermal bridging
continuous insulation
ductile
alloy
heat treatment
quench
temper
anneal
cold working
galvanize
electroplating
anodize
casting
rolling
extrusion
forging
stamping
drawing
machining
milling
lathe
drilling
drill press
tap
die
flame-cutting torch
plasma cutting
laser cutting
sheet metal brake
brake metal
welding
brazing
soldering
brittle
Types 304, 316, 410 stainless steel
die casting
galvanic protection
hot-dip galvanizing
electrogalvanizing
mechanical galvanizing

Review Questions

1. How are light gauge steel framing members manufactured?

2. How do the details for a house framed with light gauge steel members differ from those for a similar house with wood platform framing?

3. What special precautions should you take when detailing a steel-framed building to avoid excessive conduction of heat through the framing members?

4. If a building framed with light gauge steel members must be totally noncombustible, what materials would you use for subflooring and wall sheathing?

5. What is the advantage of a prescriptive building code for light gauge steel framing?

6. Compare the advantages and disadvantages of wood light frame construction and light gauge steel frame construction.

Exercises

1. Convert a set of details for a wood light frame house to light gauge steel framing.

2. Visit a construction site where light gauge steel studs are being installed. Grasp an installed stud that has not yet been sheathed, at chest height, and twist it clockwise and counterclockwise. How resistant is the stud to twisting? How is this resistance increased as the building is completed?

3. On this same construction site, make sketches of how electrical wiring, electric fixture boxes, and pipes are installed in metal framing.

Selected References

American Iron and Steel Institute. *AISI Cold-Formed Steel Design Manual*. Chicago, 2017.

This engineering reference work contains structural design tables and procedures for light gauge steel framing.

International Code Council. *International Residential Code for One- and Two-Family Dwellings*. Falls Church, VA, 2002.

This code incorporates full design information and other code provisions, applicable throughout most of the United States, for light gauge steel frame residential construction.

Websites

American Galvanizers Association: galvanizeit.org

American Iron and Steel Institute (AISI): www.steel.org

BuildSteel: www.buildsteel.org

Center for Cold-Formed Steel Structures (CCFSS): www.ccfssonline.org

ClarkDietrich Building Systems: www.clarkdietrich.com

Cold-Formed Steel Engineers Institute (CFSEI): www.cfsei.org

Steel Framing Alliance: www.steelframing.org

Steel Stud Manufacturers Association (SSMA): www.ssma.com

The "camera obscura" is an ancient device: a room-sized projector used to display views of the room's surroundings within the camera, where these images may be viewed by the camera's occupants. In undertaking the Camera Obscura at Mitchell Park, SHoP Studio accepted the nostalgic theme of the client's program and added to it its own interests in developing state-of-the-art design and construction methods (Figures A – D).

SHoP designed and documented the Camera Obscura entirely in the form of a three-dimensional digital model. Beyond facilitating the project's unconventional geometry, the use of

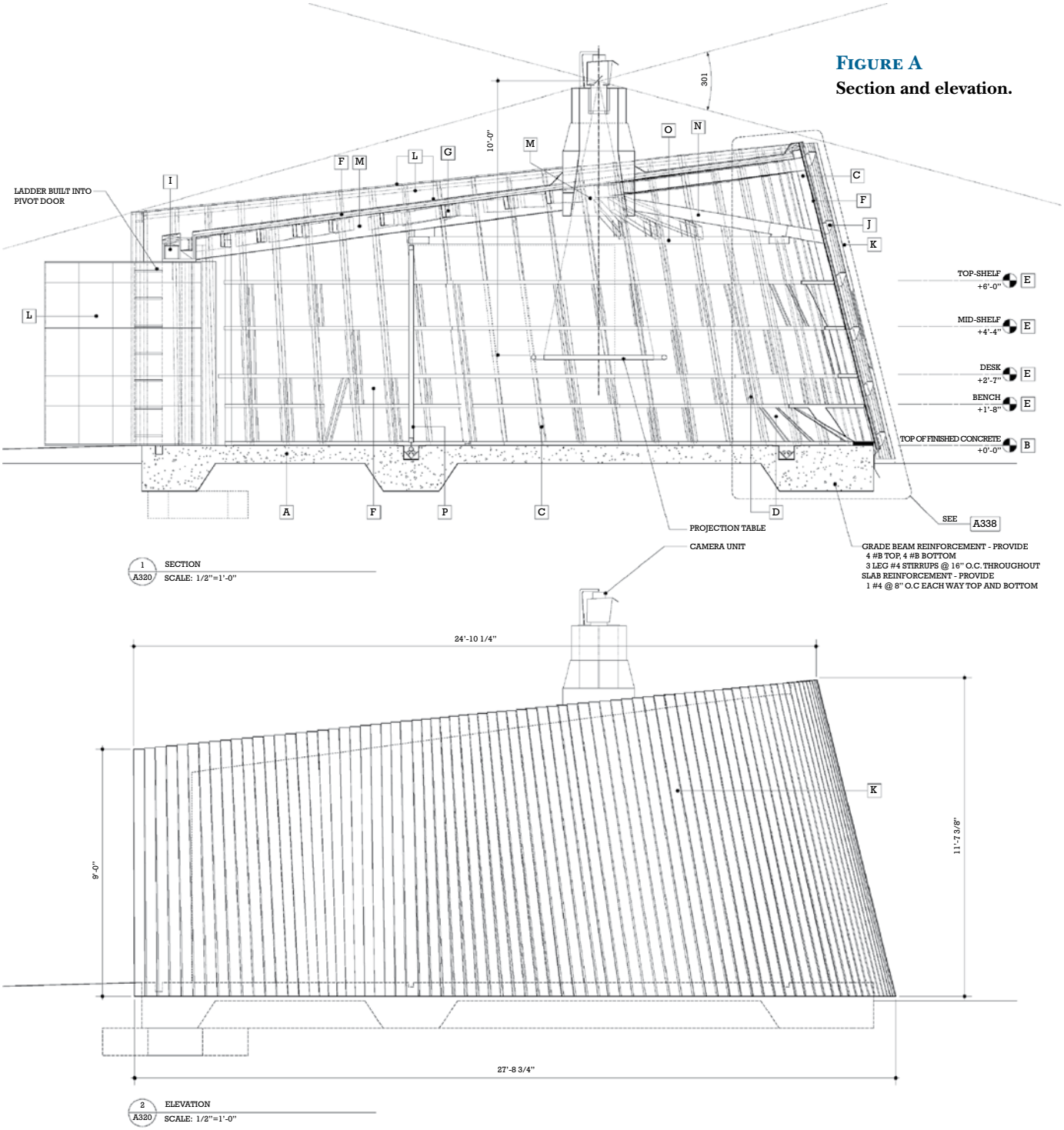


FIGURE A
Section and elevation.

digital modeling created significant opportunities for changing the way in which this project would be built and altering the architect's contribution to that process.

As a consequence of the digital model, much of the traditional construction-phase shop drawing preparation process was stood on its head. Instead of the fabricator preparing drawings for review by the architect/engineer team, the design model created by SHoP was used to generate templates that were supplied by the architect in digital form to the fabricator. The fabricator used these templates to drive automated machinery that transformed raw materials stock to cut, formed, and drilled components. Pieces were delivered to the construction site individually prelabeled, ready for assembly in the final structure.

FIGURE B

Cutting templates derived from the digital model.

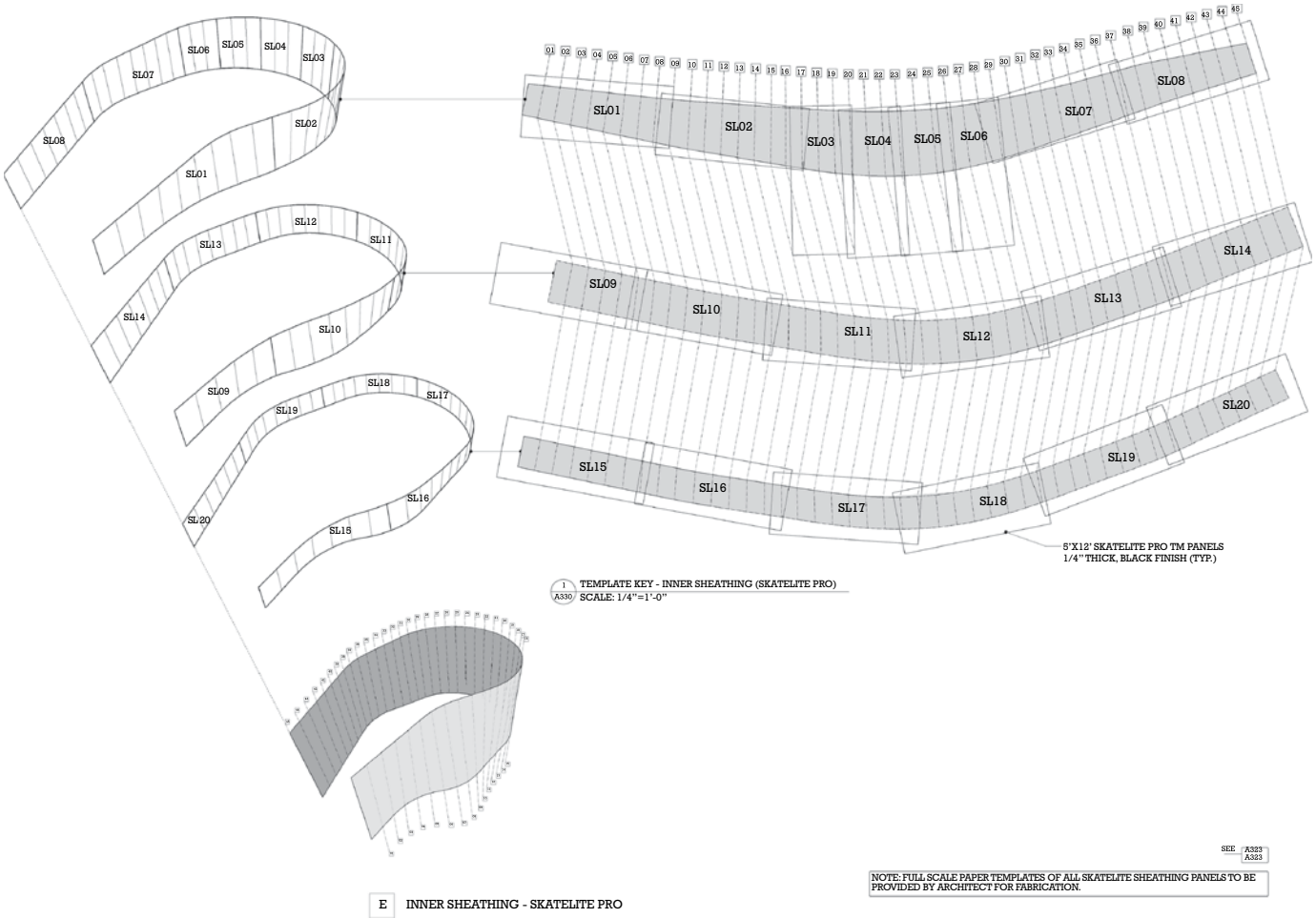
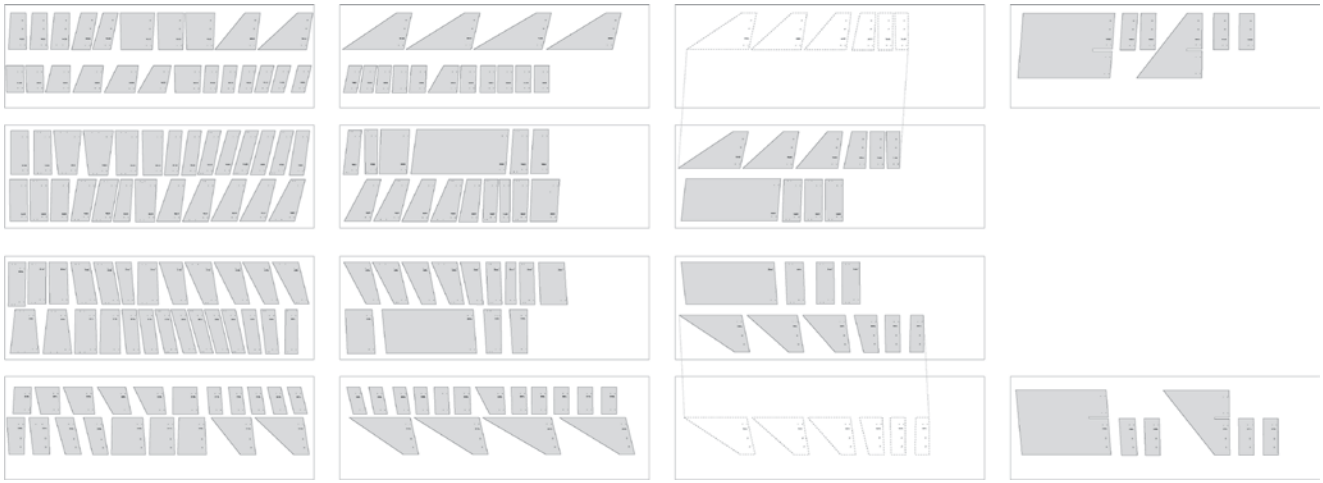


Figure C
Individually sized and shaped aluminum fins.



The building model also allowed SHoP to explore the possibilities of customization beyond what is practical with more conventional design methods. In the Camera Obscura, many of the building pieces were unique in shape and were intended for use in a single predetermined location within the building. If this proposition were undertaken using conventional construction methods, it would imply significant cost premiums. By capitalizing on the descriptive capabilities of the model coupled with automated fabrication, the costs to produce these items and to organize their assembly can be made competitive with traditional construction.

SHoP also used the digital building model to generate construction drawings that communicated how the building would be assembled in the field. For example, exploded assembly diagrams were used to study and illustrate the sequences in which systems were constructed. Cutting patterns were organized to minimize cutting time and material waste. Templates were plotted full size on paper and delivered to the building site to assist with construction layout.

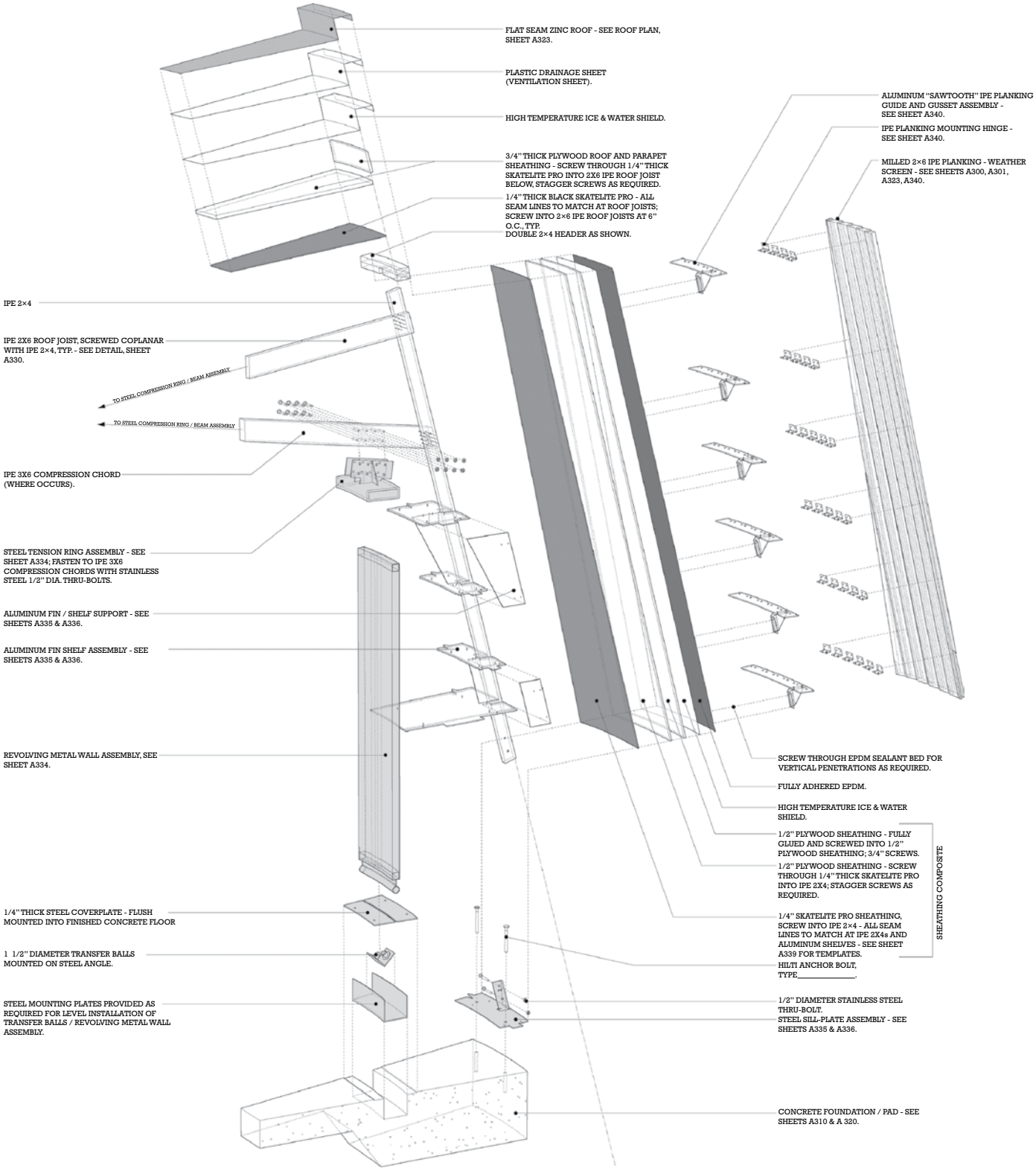
SHoP's interest in creatively exploring the means of construction carried with it additional responsibilities. Because SHoP provided templates for forming various components, it assumed greater responsibility for ensuring that these components would fit properly when assembled in the field. As a consequence, SHoP worked closely with fabricators and suppliers to educate themselves regarding both the potential capabilities and the limitations of the materials with which they designed. In some instances, material properties, such as the practical bend radii of metals of various gauges, were built into the parameters of the digital model itself. Full-size mockups could be constructed on site to verify assembly concepts and tolerances prior to fabricating the bulk of the project's components. And as with any design firm committed to improving its professional capabilities, the lessons SHoP learned from completed work are conscientiously applied to new projects.

SHoP's goal was to connect the tools of design with the techniques of construction. Note that all images shown here are taken from actual construction drawings, for a project awarded through a competitive, public bid process. With the innovative application of new design tools and a willingness to challenge the conventional professional boundaries, SHoP aims to open up new architectural possibilities.

Special thanks to SHoP/Sharples Holden Pasquarelli, and William Sharples, principal, for assistance with the preparation of this case study.

Figure D

Assembly diagram.



2 / A338 EXPLODED AXONOMETRIC - ASSEMBLY DETAILS
NOT TO SCALE

13

Concrete Construction

- History
- Cement and Concrete
  - Cement
  - Sustainability and Concrete Construction
  - Aggregates and Water
  - Supplementary Cementitious Materials
  - Concrete Admixtures
- Making and Placing Concrete
  - Proportioning Concrete Mixes
  - Handling and Placing Concrete
  - Curing Concrete
- Formwork
- Reinforcing
  - The Concept of Reinforcing
  - Steel Bars for Concrete Reinforcement
  - Welded Wire Reinforcement
  - Fabrication and Erection of Reinforcing Bars
  - Reinforcing a Simple Concrete Beam
  - Reinforcing a Continuous Concrete Beam
  - Reinforcing Structural Concrete Slabs
  - Two-Way Slab Action
  - Reinforcing Concrete Columns
  - Fibrous Reinforcing
- Concrete Creep
- Prestressing
  - Pretensioning
  - Posttensioning
- Concrete Standards
- Innovations in Concrete

The Chapel of St. Ignatius, Seattle University, designed by architect Steven Holl. Holl creates a striking composition of precisely detailed tilt-up concrete wall panels and architectural sheet metal roofing. *(Photo by Joseph Iano.)*

Concrete is the universal material of construction. According to the World Business Council for Sustainable Development, concrete is, after water, the most widely used material on earth. The raw ingredients for its manufacture are readily available in almost every part of the globe, and concrete can be made into buildings with tools ranging from a primitive shovel to a computerized precasting plant. Concrete does not rot or burn; it is relatively low in cost; and it can be used for every building purpose, from lowly pavings to sturdy structural frames to handsome exterior claddings and interior finishes.

Concrete is also the only major structural material commonly manufactured on site; it has no form of its own; and it has no useful tensile strength. Before its potential can be realized, the designer and builder must learn to produce concrete of consistent and satisfactory quality, to combine concrete skillfully with steel reinforcing to bring out the best structural characteristics of each material, and to mold and shape it to forms appropriate to its qualities and to our building needs.

History

The ancient Romans, while quarrying limestone for mortar, accidentally discovered a silica- and alumina-bearing mineral on the slopes of Mount Vesuvius that, when mixed with limestone and burned, produced a cement that exhibited a unique property: When mixed with water and sand, it produced a mortar that could harden underwater as well as in the air. In fact, it was stronger when it hardened underwater. This mortar was also harder, stronger, much more adhesive, and cured much more quickly than the ordinary lime mortar to which they were accustomed. In time, it not only became the preferred mortar for use in all their building projects, but it also began to alter the character of Roman construction. Masonry of stone or brick came to be used to build only the surface layers of piers, walls, and vaults, and the hollow interiors were filled entirely with large volumes of the new type of mortar (Figure 13.2). We now know that this mortar contained all the essential ingredients of modern portland cement and that the Romans were the inventors of concrete construction.

Knowledge of concrete construction was lost with the fall of the Roman Empire, not to be regained until the latter part of the 18th century, when a number of English inventors began experimenting with both natural and artificially produced cements. Joseph Aspdin, in 1824, patented an artificial cement that he named *portland cement*, after English Portland limestone, whose durability as a building stone was legendary. His cement was soon in great demand, and the name "portland," for the cementitious component of concrete, remains in use today.

Reinforced concrete, in which steel bars are embedded to resist tensile forces, was developed in the 1850s by several people simultaneously. Among them were the Frenchman J. L. Lambot, who built several reinforced concrete boats in Paris in 1854, and an American, Thaddeus Hyatt, who made and tested a number of reinforced concrete beams. But the combination of steel and concrete did not come

Figure 13.1

At the time concrete is placed, it has no form of its own. This bucket of fresh, wet concrete was filled on the ground by a transit-mix truck and hoisted to the top of the building by a crane. The worker at the right has opened the valve in the bottom of the bucket to discharge the concrete. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

into widespread use until a French gardener, Joseph Monier, obtained a patent for reinforced concrete flower pots in 1867 and went on to build concrete water tanks and bridges of the new material. By the end of the 19th century, engineering design methods had been developed for structures of reinforced concrete and a number of major structures had been built. By this time, the earliest experiments in prestressing (placing the reinforcing steel under tension before the structure supports a load) had also been carried out, although it remained for Eugene Freyssinet in the 1920s to establish a scientific basis for the design of prestressed concrete structures.

Cement and Concrete

Concrete is a rocklike material produced by mixing coarse and fine *aggregates*, portland cement, and water and allowing the mixture to harden. *Coarse aggregate* is normally gravel or crushed stone, and *fine aggregate* is sand. Portland cement, hereafter referred to simply as cement, is a fine gray powder. During the hardening, or *curing*, of concrete, the cement combines chemically with water to form strong crystals that bind the aggregates together, a process called *hydration*. During this process, considerable heat, called *heat of hydration*, is given off. In addition, especially as excess water evaporates from the concrete, the concrete shrinks slightly, a phenomenon referred to as *drying shrinkage*. The curing process, and the gradual increase in the strength of the concrete that occurs with it, does not end abruptly unless it is artificially interrupted. Rather, it tapers off over long periods of time, though, for practical purposes, concrete is normally considered cured and at full design strength after 28 days.

In properly formulated concrete, the majority of the volume consists of coarse and fine aggregate, proportioned and graded so that the fine particles fill the spaces between the coarse ones (Figure 13.3). Each particle is completely coated with a paste of cement and water that bonds it fully to the surrounding particles.

Figure 13.2
Hadrian's Villa, a large palace built near Rome between AD 125 and 135, used unreinforced concrete extensively for structures such as this dome. *(Photo by Edward Allen.)*

Cement

Portland cement may be manufactured from any of a number of raw materials, provided that they are combined to yield the necessary amounts of lime, iron, silica, and alumina. Lime is commonly furnished by limestone, marble, marl (a sedimentary rock), or seashells. Iron, silica, and

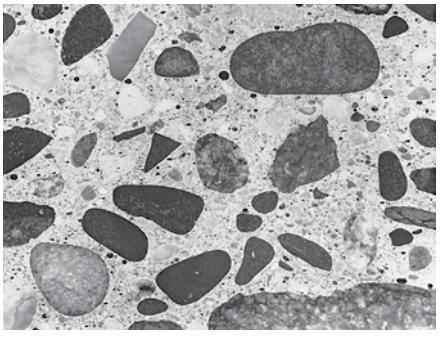


Figure 13.3
Photograph of a polished cross section of hardened concrete, showing the close packing of coarse and fine aggregates and the complete coating of every particle with cement paste. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

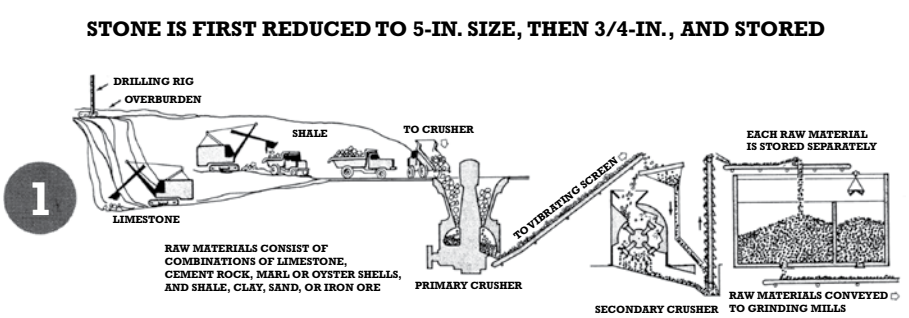
alumina may be provided by clay or shale. The exact ingredients depend on what is readily available, and the recipe varies from one geographic locale to another, often including slag or flue dust from iron furnaces, chalk, sand, ore washings, bauxite, and other minerals. To make portland cement, the selected constituents are crushed, ground, proportioned, and blended. Then they are conducted through a long, rotating kiln at temperatures of 2600 to 3000 degrees Fahrenheit (1400 to 1650°C) to produce *clinker* (Figures 13.4 and 13.5). After cooling, the clinker is pulverized to a powder finer than flour. Usually at this stage a small amount of gypsum is added to act as a retardant during the later concrete curing process. This finished powder, portland cement, is either packaged in bags or shipped in bulk. In the United States, a standard bag of cement contains 1 cubic foot (0.09 m^2) of volume and weighs 94 pounds (43 kg).

The quality of portland cement is established by ASTM C150, which identifies eight types:

Type I	Normal
Type IA	Normal, air entraining
Type II	Moderate resistance to sulfate attack
Type IIA	Moderate sulfate resistance, air entraining
Type III	High early strength
Type IIIA	High early strength, air entraining
Type IV	Low heat of hydration
Type V	High resistance to sulfate attack

Type I cement is used for most purposes in construction. Types II and V are used where the concrete will be in contact with water that has a high concentration of sulfates. Type III hardens more quickly than the other types and is employed in situations where a reduced curing period is desired (as may be the case in cold weather), in the precasting of concrete structural elements, or when the construction schedule must be accelerated. Type IV is used in massive structures such as dams, where

STEPS IN THE MANUFACTURE OF PORTLAND CEMENT



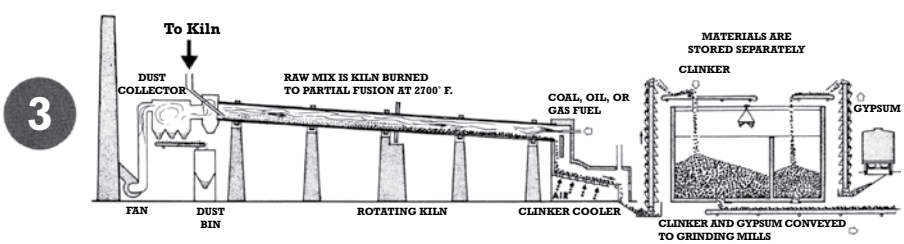


FIGURE 13.4
A rotary kiln manufacturing cement clinker. The blended raw ingredients for cement are introduced into the kiln's higher end, top right in this photograph. As the kiln rotates, the ingredients slowly tumble downward toward the lower, far end. Heated air is introduced into the kiln through the large round ducts clustered around the kiln's lower end. *(Photo by Joseph Iano.)*

the heat emitted during curing may raise the temperature of the concrete to damaging levels. Most cement that is manufactured in North America is designated as Type I/II, meaning it meets the requirements of both these types.

Air-entraining cements contain ingredients that cause microscopic air bubbles to form in the concrete during mixing (Figure 13.6). These bubbles, which usually comprise 2 to 8 percent of the volume of the finished concrete, improve workability during placement of the concrete and, more importantly, greatly increase the resistance of the finished concrete to damage caused by repeated cycles of freezing and thawing. Air-entrained concrete is commonly used for pavings and exposed architectural concrete in cold climates. With appropriate adjustments in the formulation of the mix, air-entrained concrete can achieve the same strength as normal concrete.

White portland cement is produced by controlling the quantities of certain minerals, such as oxides of iron and manganese, found in the ingredients of cement, that contribute to cement's usual gray color. White portland cement is used for architectural applications to produce concrete that is lighter and more uniform in color or, when combined with other coloring agents, to enhance the appearance of integrally colored concrete.

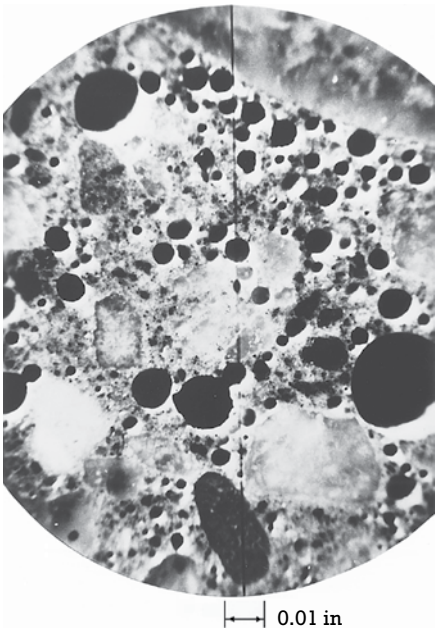
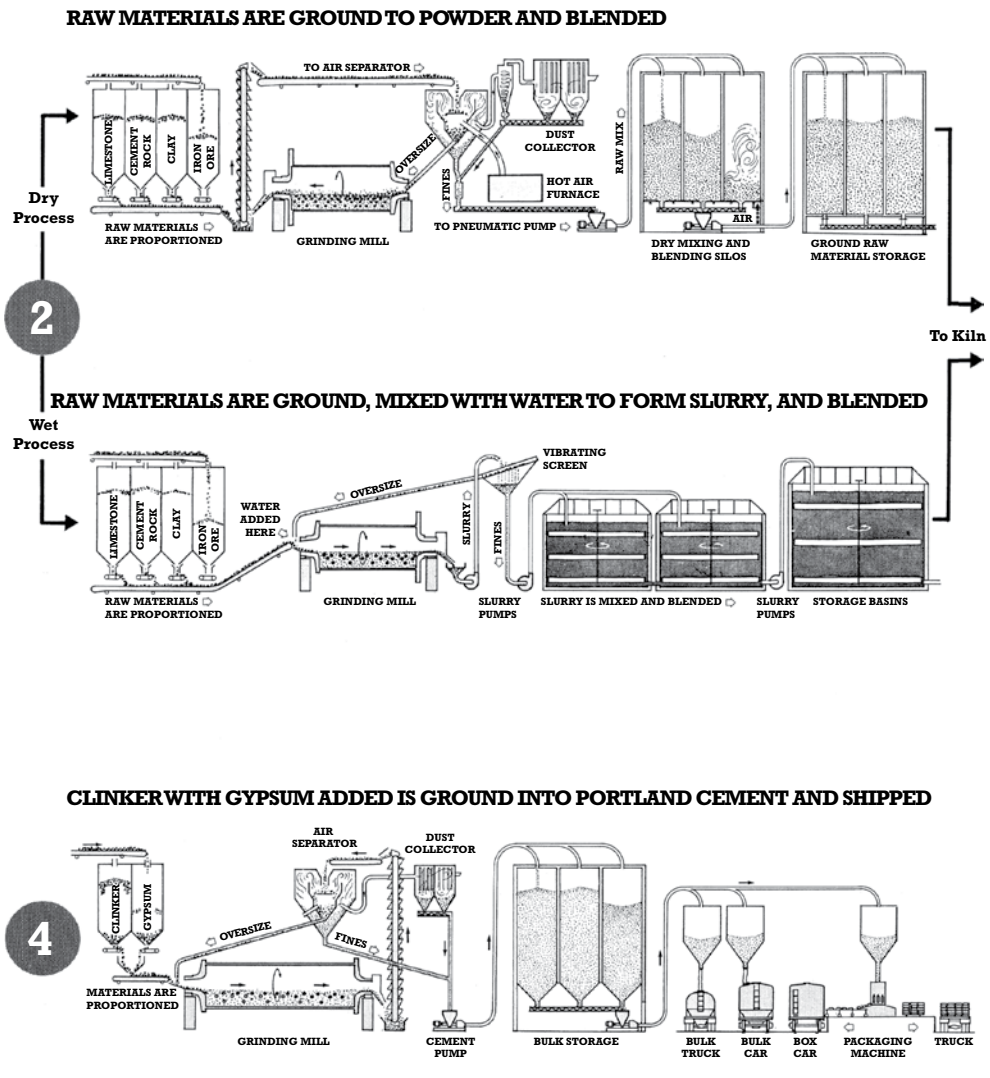


FIGURE 13.6
A photomicrograph of a small section of air-entrained concrete shows the bubbles of entrained air (0.01 inch equals 0.25 mm). *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

FIGURE 13.5
Steps in the manufacture of portland cement. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; drawings from Portland Cement Association, Skokie, IL.)*



Sustainability and Concrete Construction

Over 10 billion tons (9 billion metric tons) of concrete are produced worldwide each year. The concrete industry is the largest consumer of natural resources in the world.

Sustainable Sites

- Lighter-colored concrete paving reflects more solar radiation than darker asphalt paving, resulting in lower surface temperatures and reduced urban heat island effects.
- Pervious concrete can be used to make porous pavings that allow stormwater to filter into the ground, helping to recharge aquifers, reduce stormwater runoff, and reduce waterway pollution.
- Photocatalytic agents can be added to concrete used in the construction of roads and buildings. In the presence of sunlight, the concrete chemically breaks down carbon monoxide, nitrogen oxide, benzene, and other air pollutants.

Energy Performance

- Concrete's thermal mass can be exploited to reduce building heating and cooling costs by storing excess heat during overheated periods of the day or week and releasing it back to the interior of the building during underheated periods.

Building and Material Life-Cycle Impacts

- A National Ready Mixed Concrete Association EPD reports the following North American industry average cradle-to-gate impacts per cubic meter (35 cu ft) of concrete ranging in compressive strength from 2500 to 8000 psi (17 to 55 MPa). Generally, greater impacts correlate with higher-strength mixes and less use of supplementary cementitious materials:

Nonrenewable primary energy consumption	1700–4600 MJ (1.6–4.4 million BTU)
Global warming potential	190–620 kg (410–1400 lb) CO_2 eq.
Fresh water consumption	250 L (66 gal)

- Concrete is a durable material that can be used to construct buildings that are long-lasting and suitable for adaptation and reuse, thereby reducing the environmental impacts of building demolition and new construction.
- When a concrete building is demolished, its reinforcing steel can be recycled.
- Concrete is 100 percent recyclable. For example, fragments of demolished concrete can be crushed, sorted, and used as aggregates for new concrete. At present, however, most demolished concrete is buried on site, used to fill other sites, or dumped in a landfill.

Material and Production Attributes

- Waste materials such as crushed, recycled glass and used foundry sand can substitute for a portion of the conventional aggregates in concrete.
- The production of portland cement consumes the largest share of energy in the concrete manufacturing process, accounting for about 85 percent of the total energy required.
- For every ton of cement clinker produced, almost a ton of carbon dioxide is released into the atmosphere, accounting for roughly 7 percent of all carbon dioxide gas generated by human activities worldwide.

Aggregates and Water

Because aggregates make up roughly three-quarters of the volume of concrete, the strength of a concrete is heavily dependent on their quality. Aggregates for concrete must be strong, clean, resistant to freeze-thaw deterioration, chemically stable, and properly graded for size distribution. An aggregate that is dusty or muddy will contaminate the cement paste with inert particles that weaken it. An aggregate that contains any of a number of chemicals, from sea salt to organic compounds, can cause problems ranging from corrosion of reinforcing steel to retardation of the curing process and weakening of the concrete. A number of standard ASTM laboratory tests are used to assess the various qualities of aggregates (Figure 13.7).

Size distribution of aggregate particles is important because a range of sizes must be included and properly proportioned in the concrete mix to achieve close packing of the particles. A concrete aggregate is graded for size using a standard assortment of sieves with diminishing mesh spacings, then weighing the percentage of material that passes through each sieve, in the same manner as described in Chapter 2. Aggregates must also be sized so that the largest particle in the mix is small enough to pass easily between reinforcing bars and fit easily into the formwork. In general, aggregate should be no larger than three-fourths of the clear spacing between bars or one-third the depth of a slab.

- Adding (up to 15 percent by mass) finely ground limestone to portland cement can reduce raw materials consumption, energy consumption, carbon dioxide emissions, and cement dust generation during cement manufacturing, with little to no adverse effect on cement properties.
- By replacing portland cement in concrete with supplementary cementitious materials, such as fly ash, silica fume, and blast furnace slag, the carbon dioxide emissions and energy consumption impacts of concrete production can be significantly reduced.
- Over concrete's lifetime, it can reabsorb as much as 40 to 50 percent of the carbon dioxide released during the cement manufacturing process.
- In North America, reinforcing bars are made almost entirely from recycled steel scrap.

Unhealthful Materials and Emissions

- Concrete itself is not normally associated with indoor air quality problems.

Responsible Industry Practices and Social Impacts

- The quarrying of the raw materials for concrete in open pits can result in soil erosion, pollutant runoff, habitat loss, and ugly scars on the landscape.
- Sand and crushed stone come from abundant sources in many parts of the world, but high-quality aggregates are becoming scarce in some countries.
- Some geographic regions are running out of limestone resources.
- Water suitable for use in concrete is scarce in some regions.
- In the past 40 years, U.S. cement manufacturers have reduced the amount of energy expended in cement production by 40 percent.
- Over the same time frame, the emission of particulates from cement production has been reduced by more than 90 percent.
- Cement kilns can burn large quantities of waste materials, such as used motor oil, discarded car tires, and soils contaminated by fuel oil, that are otherwise difficult to dispose of. At the same time, a cement manufacturing plant can, if efficiently operated, generate virtually no solid or liquid wastes itself.
- U.S. EPA Energy Star programs, implemented in cooperation with cement and concrete manufacturers, are working to continue to improve energy efficiency in these industries.
- The Concrete Sustainability Council provides independent, third-party certification of concrete manufacturer sustainable practices for raw materials extraction, manufacturing processes, and related social, environmental, and human rights considerations.
- Technologies under development aim to further reduce or eliminate carbon dioxide emissions from cement and concrete production. Carbon dioxide emissions from aluminosilicate cement manufacturing are as much as 80 to 90 percent less than those of portland cement. Cement made from magnesium produces a material that is carbon negative, absorbing significantly more carbon over its lifetime than is emitted during its manufacture. Other efforts aim to develop concrete replacement materials that, rather than being a source of carbon emissions, consume carbon in their manufacture and can act as mechanisms for carbon capture and sequestration.

For very thin slabs and toppings, a ⅜-inch (9-mm) maximum aggregate diameter is often specified. A ¾-inch or 1½-inch (19-mm or 38-mm) maximum size is common for much slab and structural work. Aggregate with diameters up to 6 inches (150 mm) are used in dams and other massive structures.

Lightweight aggregates are used for various special types of concrete. *Structural lightweight aggregates* are made from minerals such as shale. The shale is crushed to the desired particle sizes, then heated in an oven to a temperature at which it becomes plastic in consistency. The small amount of water that occurs

FIGURE 13.7
Taking a sample of coarse aggregate from a crusher yard for testing. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

naturally in the shale turns to steam and expands the softened particles like popcorn. Concrete made from this *expanded shale aggregate* has a density about 25 percent less than that of normal concrete, yet it is nearly as strong. Nonstructural lightweight concretes are made for use in insulating roof toppings that have densities only one-fourth to one-sixth that of normal concrete. The aggregates in these concretes are usually expanded mica (*vermiculite*) or expanded volcanic glass (*perlite*), both produced by processes much like that used to make expanded shale. However, both of these aggregates are much less dense than expanded shale, and the density of the concretes in which they are used is further reduced by admixtures that entrain large amounts of air during mixing.

ASTM standard C1602 defines the requirements for mixing water for concrete. Generally, *water* must be free of harmful substances, especially organic material, clay, and salts such as chlorides and sulfates. Water that is suitable for drinking has traditionally been considered suitable for making concrete.

Supplementary Cementitious Materials

Various mineral products, called *supplementary cementitious materials (SCMs)*, may be added to concrete mixtures as a substitute for some portion of the portland cement to achieve a range of benefits. Supplementary cementitious materials are classified as either pozzolans or hydraulic cements.

Pozzolans are materials that react with the calcium hydroxide in wet concrete to form cementing compounds. They include:

- *Fly ash*, a fine powder that is a waste product from coal-fired power plants, increases concrete strength, decreases permeability, increases sulfate resistance, reduces temperature rise during curing, reduces the amount of mixing water needed, and improves pumpability and workability of concrete. Fly ash also reduces concrete drying shrinkage.
- *Silica fume*, also known as *microsilica*, is a powder that is approximately 100 times finer than portland cement, consisting mostly of silicon dioxide. It is a byproduct of electronic semiconductor chip manufacturing. When added to a concrete mix, it produces extremely high-strength concrete that also has very low permeability.
- *Natural pozzolans*, mostly derived from shales or clays, are used for purposes such as reducing the internal temperature of curing concrete, reducing the reactivity of concrete with aggregates containing sulfates, or improving the workability of concrete.
- *High-reactivity metakaolin* is a unique white-colored natural pozzolan that enhances the brilliance of white or colored concrete while also improving the material's workability, strength, and density. These characteristics make it especially well suited as an ingredient in exposed architectural concrete applications where appearance and finish quality are critical.

Blast furnace slag (also called *slag cement*), a byproduct of iron manufacture, is a *hydraulic cement*, meaning that, like portland cement, it reacts directly with water to form a cementitious compound. It may be added to concrete mixes to improve workability, increase strength, reduce permeability, reduce temperature rise during curing, and improve sulfate resistance.

Supplementary cementitious materials may be added to portland cement during the cement manufacturing process, in which case the resulting product is called a *blended hydraulic cement* (ASTM C595), or they may be added to the concrete mix at the batch plant. The use of these materials also enhances the sustainability of concrete by reducing reliance on more energy-intensive portland cement and, in many cases, by making productive use of waste products from other industrial manufacturing processes. Half or more of the concrete produced in North America includes some supplementary cementitious materials in its mix.

Concrete Admixtures

Chemical ingredients other than cement and other cementitious materials, aggregates, and water, broadly referred to as concrete *admixtures*, may be added to concrete to alter its properties in various ways:

- *Air-entraining admixtures* increase the workability of the wet concrete, reduce freeze-thaw damage in hardened concrete, and, when used in larger amounts, create very lightweight nonstructural concretes with thermal insulating properties.
- *Water-reducing admixtures* allow a reduction in the amount of mixing water while retaining the same workability, which results in a higher-strength concrete.
- *High-range water-reducing admixtures*, also known as *superplasticizers*, are organic compounds that transform a stiff concrete mix into one that flows freely into the forms. They are used either to facilitate placement of concrete under difficult circumstances or to reduce the water content of a concrete mix so as to increase its strength.
- *Accelerating admixtures* cause concrete to cure more rapidly, and *retarding admixtures* slow its curing to allow more time for working with the wet concrete.
- *Workability agents* improve the plasticity of wet concrete to make it easier to place in forms and finish. They include pozzolans and air-entraining admixtures, along with certain fly ashes and organic compounds.
- *Shrinkage-reducing admixtures* reduce drying shrinkage and the cracking that results therefrom.
- *Corrosion inhibitors* are used to reduce rusting of reinforcing steel

in structures that are exposed to road deicing salts or other corrosion-causing chemicals.

- *Freeze protection admixtures* allow concrete to cure satisfactorily at temperatures as low as 20 degrees Fahrenheit (7°C).
- *Extended set-control admixtures* may be used to delay the curing reaction in concrete for any period up to several days. They include two components: The stabilizer component, added at the time of initial mixing, defers the onset of curing indefinitely; the activator component, added when desired, reinitiates the curing process.

Coloring agents are dyes and pigments used to alter and control the color of concrete for building components whose appearance is important.

Making and Placing Concrete

The quality of cured concrete is measured by any of several criteria, depending on its end use. For structural columns, beams, and slabs, compressive strength and stiffness are important. For pavings and floor slabs, flatness, surface smoothness, and abrasion resistance are also important. For pavings and exterior concrete walls, a high degree of weather resistance is required. Watertightness is important in concrete tanks, dams, and walls. Regardless of the criterion to which one is working, however, the rules for making high-quality concrete are much the same: Use clean, sound ingredients; mix them in the correct proportions; handle the wet concrete properly; and cure the concrete thoroughly under controlled conditions.

Proportioning Concrete Mixes

The starting point of any mix design is to establish the desired workability characteristics of the wet concrete, the physical properties of the cured concrete, and the acceptable cost of the concrete, keeping in mind that there is no need to spend money to make concrete better than it has to be for a given application.

Concrete strength is routinely varied to suit the needs of the application. Concretes with ultimate compressive strengths as low as 2000 psi (15 MPa) are satisfactory for some foundation elements while those in the range of 3000 to 5000 psi (20 to 35 MPa) find extensive use throughout building structures. Concretes with compressive strengths of 8000 psi (55 MPa) or greater are called *high performance concretes* (*HPCs*). They are used where greater strength and durability are required, but at greater cost and with more stringent requirements for production controls and testing. Concretes with compressive strengths of 17,000 psi (120 MPa) or more, called *ultra-high performance concretes* (*UHPCs*), are used in tall building structures or where this material's greater flexural strength and ductility are advantageous. Throughout these strength ranges, acceptable workability, important to the successful placement and finishing of wet concrete, must also be maintained.

Given a proper gradation of satisfactory aggregates, the strength of cured concrete is primarily dependent on the amount of cement in the mix and on the *water–cement (w-c) ratio.* Although a proportion of water is required as a reactant in the curing of concrete, much more must be added to give the wet concrete the necessary fluidity and plasticity for placing and finishing. The extra water eventually evaporates from the concrete, leaving microscopic voids that reduce the strength and surface qualities of the concrete (Figure 13.8). For common concrete applications, water–cement ratios range from about 0.45 to 0.60 by weight, meaning that the weight of the water in the mix does not exceed 45 to 60 percent of the weight of the cement. Relatively high water–cement ratios are often favored by concrete workers, because they produce a fluid mixture that is easy to place in the forms, but such a mix may be deficient in strength and surface qualities. Lower water–cement ratios make concrete that is denser and stronger and that shrinks less during curing. However, without air-entraining or water-reducing admixtures, such a mix may not flow easily into the forms or may finish poorly. It is important that concrete be formulated with the right quantity of water for each situation, enough to ensure workability but not enough to adversely affect the properties of the cured material.

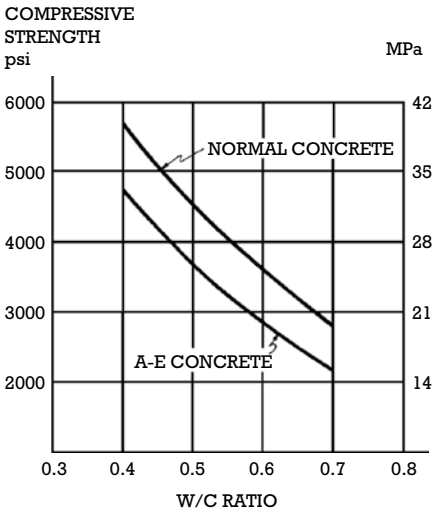


Figure 13.8
The effect of the water–cement ratio on the strength of concrete. "A-E concrete" refers to air-entrained concrete.
(Reprinted with permission of the Portland Cement Association from Design and Control of Concrete Mixtures, *12th ed.; graph from Portland Cement Association, Skokie, IL.)*

Most concrete in North America is proportioned at central batch plants, using laboratory equipment and engineering knowledge to produce concrete of the proper quality for each project. The concrete is *transit mixed* en route in a rotating drum on the back of a truck so that it is ready to pour by the time it reaches the job site (Figures 13.9 and 13.10). For very small jobs, concrete may

FIGURE 13.9
Charging a transit-mix truck with measured quantities of cement, aggregates, admixtures, and water at a central batch plant. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

FIGURE 13.10
A transit-mix truck discharges its concrete, which was mixed en route in the rotating drum, into a truck-mounted concrete pump, which forces it through a hose to the point in the building at which it is being poured. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

be mixed at the job site, either in a small power-driven mixing drum or on a flat surface with shovels. For these small jobs, where the quality of the finished concrete generally does not have to be precisely controlled, proportioning is usually done by rule of thumb. Typically, the dry ingredients are measured volumetrically, using a shovel as a measuring device, in proportions such as one shovel of cement to two of sand to three of gravel, with enough water to make a wet concrete that is neither soupy nor stiff.

Each load of transit-mixed concrete is delivered with a certificate from the batch plant that lists its ingredients and their proportions. As a further check on quality, a *slump test* may be performed at the time of pouring to determine if the desired degree of workability has been achieved without making the concrete too wet (Figure 13.11). For structural concrete, standard test cylinders are also poured from each truckload. Within 48 hours of pouring, the cylinders are taken to a testing laboratory, cured for a specified period under standard conditions, and tested for compressive strength (Figure 13.12). If the laboratory results are not up to the required standard, test cores are drilled from the actual members made from the questionable batch of concrete. If the strength of these core samples is also deficient, the contractor may be required to cut out the defective concrete and replace it. Frequently, test cylinders are also cast and cured on the construction site under the same conditions as the concrete in the forms; these may then be tested

FIGURE 13.11
Measuring concrete slump. The hollow metal cone is filled with concrete and tamped with the rod according to a standard procedure. The cone is carefully lifted off, allowing the wet concrete to sag, or slump, under its own weight. The slump is then measured in the manner shown. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

FIGURE 13.12
Inserting a standard concrete test cylinder into a structural testing machine, where it will be crushed to determine its strength. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

to determine when the concrete is strong enough to allow removal of forms and temporary supports.

Handling and Placing Concrete

Freshly mixed concrete is not a liquid but a *slurry*, a semistable mixture of solids suspended in liquid. If it is vibrated excessively, moved horizontally for long distances in the forms, or dropped through constrained spaces, it tends to segregate, meaning that the coarse aggregate works its way to the bottom of the form and the water and cement paste rise toward the top. The result is concrete of nonuniform and generally unsatisfactory properties. *Segregation* is prevented by depositing the concrete, fresh from the mixer, as close to its final position as possible.

When large quantities of concrete must be placed over a large area or at a great height, truck-mounted pumps with extendable booms deliver concrete to its final position (Figure 13.13). Usually, the concrete is pumped through a flexible hose. Or, fixed, rigid pipes may be temporarily installed to carry concrete over unusually long distances. The concrete mixture is designed so that it will not clog the line when it is put under pressure by the pump. Concrete can be pumped to astonishing heights and horizontal distances: For the Burj Khalifa tower in Dubai, concrete was pumped more than 1970 vertical feet (600 m).

For lesser distance and heights, concrete can be conveyed on portable conveyor belt systems. Crane-mounted buckets (Figure 13.1), powered buggies, or even hand wheelbarrows may also be used. The method selected will depend on the scale of the job and the accessibility of the work to the truck delivering the concrete. To prevent segregation, concrete dropped a distance of more than 3 to 5 feet (1 m or so) should be allowed to fall freely, without obstruction, or it should be deposited through *dropchutes* that control its fall. Concrete should also not be pushed over horizontal distances from one location to another once it has been deposited.

Once placed, concrete must be *consolidated* to eliminate trapped air and to completely fill the space around the reinforcing bars and in all corners of the formwork. This may be done by repeatedly thrusting a rod, spade, or immersion-type vibrator into the concrete at closely spaced intervals throughout the formwork. Excessive agitation of the concrete must be avoided, however, or segregation will occur.

Self-consolidating concrete (SCC), a concrete that fills forms completely without requiring vibration or any other method of consolidation, is formulated with more fine aggregates than coarse ones, a reversal of the usual proportions; it also includes special superplasticizing admixtures and, in some cases, other viscosity-modifying agents. The result is a concrete that flows freely yet does not allow its coarse aggregate to sink to the bottom of the mix. Self-consolidating concrete may be used where forms are crowded with steel reinforcing, making consolidation of stiffer conventional concrete problematic. The consistent surface characteristics and crisp edges produced by self-consolidating concrete make it well suited to the production of high-finish-quality architectural concrete. By eliminating the separate consolidation step and allowing more rapid placement, self-consolidating concrete can improve productivity in precast concrete and large-volume sitecast concrete operations. However, formwork costs for self-consolidating concrete may be higher than those for conventional concrete, as the greater fluid pressures exerted by the freely flowing material require stiffer and stronger forms.

Curing Concrete

Because concrete cures by hydration, the chemical bonding of the water and cement, and not by simple

FIGURE 13.13
A transit mixer feeds fresh concrete directly to a truck-mounted pump that delivers the concrete to an upper floor level. The end of the boom is radio controlled by an operator standing close to where the concrete is being deposited. *(Photo by Joseph Iano.)*

drying, it is essential that it be kept moist until its required strength is achieved. The curing reaction takes place over a very long period of time, but concrete is commonly designed on the basis of the strength that it reaches after 28 days. If it is allowed to dry out at any point during this time period, the strength of the resulting concrete will be reduced, and its surface hardness and durability can be adversely affected (Figure 13.14). Concrete cast in formwork is protected from dehydration on most surfaces by the formwork, but the top surfaces must be kept moist by repeatedly spraying or flooding with water, by covering with moisture-resistant sheets of paper or film, or by spraying on a curing compound that seals the surface of the concrete against loss of moisture. These measures are even more important for concrete slabs, whose large exposed surface areas make them especially susceptible to premature drying. This is a particular danger when slabs are poured in hot or windy weather, which can cause the surface of the pour to dry out and crack even before the concrete begins to cure. Temporary windbreaks may be erected, shade may be provided, evaporation retarders may be added to the concrete, and frequent fogging of the air directly over the surface of the slab with a fine spray of water may be required until the slab is hard enough to be finished and covered or sprayed with curing compound.

At low temperatures, the curing reaction in concrete proceeds much more slowly. If concrete reaches subfreezing temperatures while curing, the reaction stops completely until the temperature of the concrete rises above the freezing mark. To achieve full strength, it is important that the concrete be protected from very low temperatures or freezing until it is adequately cured. If freshly poured concrete is covered and insulated, its heat of hydration may be sufficient to maintain an adequate temperature in the concrete even at fairly low air temperatures. Under more severe conditions, the ingredients of the concrete may have to be heated before mixing, and both a temporary enclosure and a temporary source of

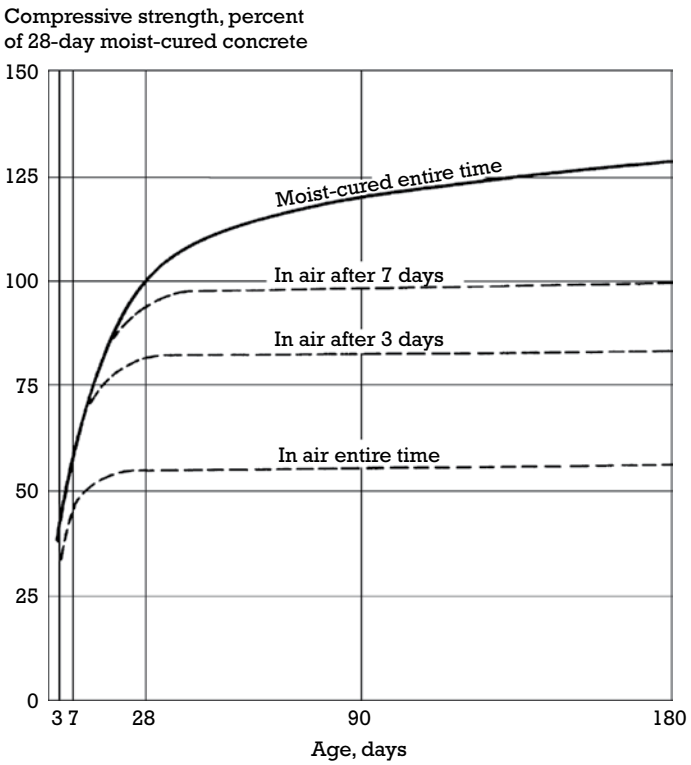


FIGURE 13.14
The growth of compressive strength in concrete over time. Moist-cured concrete is still gaining strength after six months, whereas air-dried concrete virtually stops gaining strength altogether. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; graph from Portland Cement Association, Skokie, IL.)*

heat may have to be provided during placing and curing.

In very hot weather, the hydration reaction is greatly accelerated, and concrete may begin curing before there is time to place and finish it. This tendency can be controlled by using cool ingredients and, under extreme conditions, by replacing some of the mixing water with an equal quantity of crushed ice, making sure that the ice has melted fully and the concrete has been thoroughly mixed before placing. Another method of cooling concrete is to bubble liquid nitrogen through the mixture at the batch plant.

FORMWORK

Because concrete is put in place as a shapeless slurry with no physical strength, it must be shaped and supported by *formwork* until it has cured sufficiently to support itself. Formwork is usually made of braced panels of wood, metal, or plastic. It is constructed as a negative of the shape intended for the concrete. Formwork for a beam or slab serves as a temporary working surface during the construction process and as the temporary means of support for reinforcing bars. Formwork must be strong enough to support the considerable weight and fluid pressure of wet concrete without deflection, which often requires temporary supports that are major structures in themselves. During curing, the formwork helps to retain the necessary water of hydration in the concrete. When curing is complete, the formwork must pull away cleanly from the concrete surfaces without damage either to the concrete or to the formwork, which is usually used repeatedly as a construction project progresses. This means that the formwork should have no reentrant corners that will trap or be trapped by the concrete. Any element of formwork that must be withdrawn directly from a location in which it is surrounded on four or more surfaces by concrete, such as a joist pan (Figures 14.24 and 14.25), must be tapered. Formwork surfaces that are in contact with concrete are also usually coated with a *form release compound*, an oil, wax, or plastic that prevents adhesion of the concrete to the form.

The quality of the concrete surfaces can be no better than the quality of the forms in which they are cast, and the requirements for surface quality and structural strength of formwork are rigorous. Top-grade wooden boards and resin-overlaid plywood panels are frequently used to achieve high-quality surfaces. The ties and temporary framing members that support the boards or plywood are spaced closely to avoid bulging of the forms under the high pressure of the wet concrete.

In a sense, formwork constitutes an entire temporary building that must be erected and then demolished in order to produce a second,

Figure 13.15
Casting concrete on the building site requires the construction of a complete temporary structure that will be removed once the concrete has been placed and cured. *(Photo by Joseph Iano.)*

permanent building of concrete (Figure 13.15). In fact, the cost of conventional formwork accounts for a major portion—often one-half or more—of the overall cost of a concrete building frame. This cost is one of the factors that has led to the development of *precasting*, a process in which concrete is cast in reusable forms at an industrial plant. Rigid, fully cured structural units from the plant are then transported to the job site, where they are hoisted into place and connected much as if they were structural steel shapes. The alternative to precasting, and the more usual way of building with concrete, is *sitecasting*, also called *cast-in-place construction*, in which concrete is poured into forms that are erected on the job site. In Chapters 14 and 15, formwork is shown for both sitecast and precast concrete.

Reinforcing

The Concept of Reinforcing

Concrete has no useful tensile strength (Figure 13.16). Historically, its structural uses were limited until the concept of steel reinforcing was developed. The compatibility of steel and concrete is a fortuitous accident. If the two materials had grossly different coefficients of thermal expansion, a reinforced concrete structure would tear itself apart due to repeated cycles of temperature changes. If the two materials were chemically incompatible, the steel would corrode or the concrete would be degraded. If concrete did not adhere to steel, a very different and more expensive configuration of reinforcing would be necessary. Concrete and steel, however, change dimension at nearly the same rate in response to temperature changes; steel is protected from corrosion by the alkaline chemistry of concrete; and concrete bonds strongly to steel, providing a convenient means of adapting brittle concrete to structural elements that must resist not only compression, but tension, shear, and bending as well.

The basic theory of *reinforced concrete* is simple: Put the reinforcing steel where there are tensile (stretching) forces in a structural member, and let the concrete resist the compression (squeezing) forces. This accounts fairly precisely for the location of most of the reinforcing steel that is used in a concrete structure. However, there are some important exceptions: Steel is used to resist a share of the compression in concrete columns and in beams whose depth or width must be reduced for architectural reasons. It is

Material	Strength in Tension	Strength in Compression	Modulus of Elasticity	Density
Wood (framing lumber)	270–4100 psi (1.9–28 MPa)	1400–4400 psi (9.7–31 MPa)	1,100,000–1,900,000 psi (7600–13,000 MPa)	27 pcf (430 kg/m^3)
Brick masonry (including mortar, unreinforced)	30–80 psi (0.21–0.55 MPa)	1000–4000 psi (6.9–28 MPa)	800,000–3,000,000 psi (5500–21,000 MPa)	120 pcf (1900 kg/m^3)
Structural steel	60,000–90,000 psi (415–620 MPa)	60,000–90,000 psi (415–620 MPa)	29,000,000 psi (200,000 MPa)	490 pcf (7800 kg/m^3)
Concrete (unreinforced)	300–700 psi (2.1–4.8 MPa)	3000–6000 psi (20–40 MPa)	2,000,000–6,000,000 psi (14,000–41,000 MPa)	145 pcf (2300 kg/m^3)

FIGURE 13.16

Comparative ultimate strength properties of four common structural materials: wood, brick masonry, steel, and concrete (shaded row). Concrete, like masonry, has no useful tensile strength, but its compressive strength is considerable, and when combined with steel reinforcing, it can be used for every type of structure. The ranges of values in strength and stiffness reflect variations in concrete mix properties. Specially formulated concretes are capable of substantially higher strengths than those listed in this table. Wood values are for stresses parallel to the grain of the wood.

used as column ties, discussed later in this chapter, to prevent buckling of vertical reinforcing in columns. It is used to resist cracking that might otherwise be caused by curing shrinkage, and by thermal expansion and contraction in slabs and walls.

Steel Bars for Concrete Reinforcement

Steel reinforcing bars (*rebar*) for concrete construction are hot-rolled in much the same way as structural shapes. They are round in cross section and *deformed* with surface ribs that help strengthen the bond between the bars and the concrete in which they are cast (Figures 13.17 and 13.18). At the end of the rolling line in the mill, the bars are cut to a standard length (commonly 60 feet, or 18.3 m, in the United States), bundled, and shipped to local fabricating shops.

Reinforcing bars are rolled in standard diameters. In the United States, bars are specified by a number that corresponds to eighths of an inch (3.2 mm) of bar diameter (Figure 13.19). For example, a number 6 reinforcing bar is ⅝ or ¾ inch (19.1 mm) in diameter, and a number 8 is ⅞ or 1 inch (25.4 mm) in diameter.

FIGURE 13.17

Glowing strands of steel are reduced to reinforcing bars as they snake their way through a rolling mill. *(Courtesy of Bethlehem Steel Corporation.)*

Bars larger than number 8 vary slightly from these nominal diameters in order to correspond to convenient cross-sectional areas. For several decades in the United States, reinforcing bars were also provided in "soft" metric sizes. That is, the bars were unchanged from their standard eighth-inch sizes, but they were labeled to correspond roughly to their diameter in millimeters. More recently, this practice has declined. In Canada, standard reinforcing bar sizes are given in hard metric sizes, in which the bar number corresponds with the diameter of the bar rounded to the closest 5 millimeters (Figure 13.20).

In selecting reinforcing bars for a given beam or column, the structural engineer knows from calculations the required cross-sectional area of steel that is needed in a given location. This area may be achieved with a larger number of smaller bars, or a smaller number of larger bars, in any of several combinations. The final bar arrangement is based on the physical space available in the concrete member, the required depth of concrete that must cover the reinforcing, the clear spacing required between bars to allow passage of the concrete aggregate, and the sizes and number of bars that will be most convenient to fabricate and install.

The largest share of reinforcing bars are manufactured according to ASTM standard A615 and are available in grades 40, 60, 80, and 100 corresponding to steel with yield strengths of 40,000, 60,000, 80,000, and 100,000 psi (280, 420, 550, and 690 MPa),

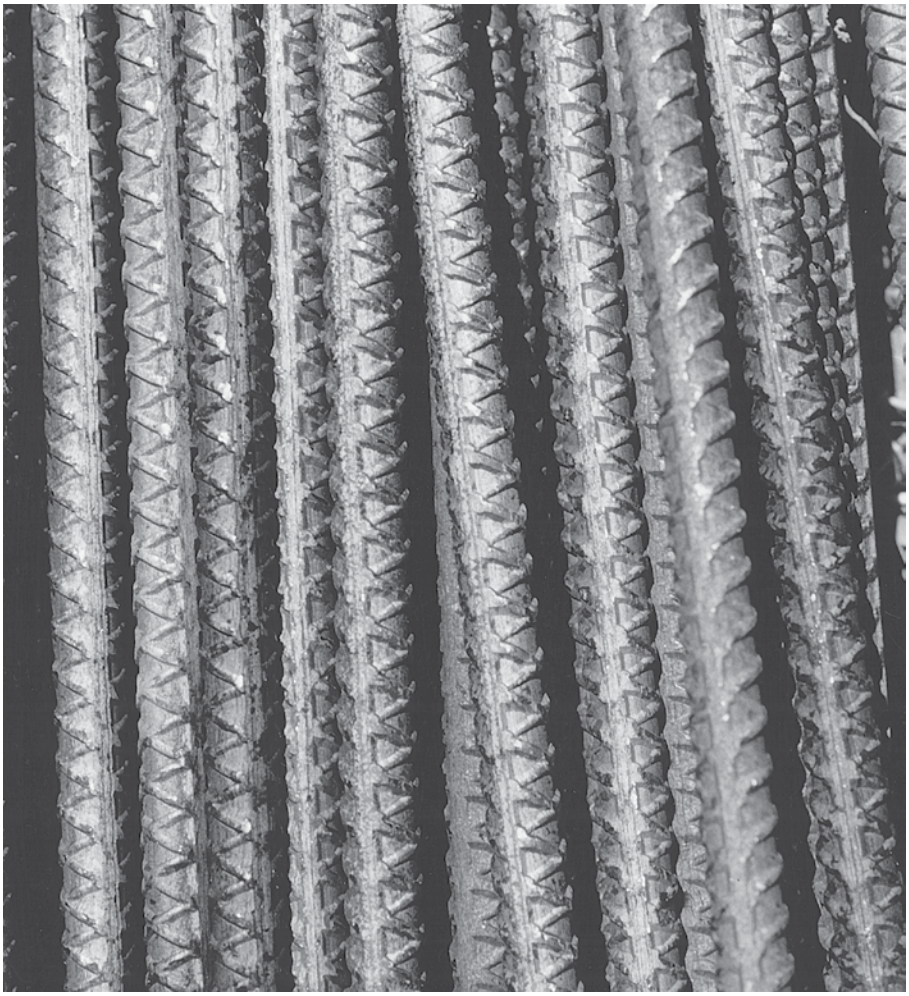


FIGURE 13.18
The deformations rolled onto the surface of a reinforcing bar help it to bond tightly to concrete. *(Photo by Edward Allen.)*

Bar Size		Nominal Dimensions					
		Diameter		Cross-Sectional Area		Weight	
American	Soft Metric	in.	mm	$in.^2$	mm^2	lb/ft	kg/m
#3	#10	0.375	9.5	0.11	71	0.376	0.560
#4	#13	0.500	12.7	0.20	129	0.668	0.944
#5	#16	0.625	15.9	0.31	199	1.043	1.552
#6	#19	0.750	19.1	0.44	284	1.502	2.235
#7	#22	0.875	22.2	0.60	387	2.044	3.042
#8	#25	1.000	25.4	0.79	510	2.670	3.973
#9	#29	1.128	28.7	1.00	645	3.400	5.060
#10	#32	1.270	32.3	1.27	819	4.303	6.404
#11	#36	1.410	35.8	1.56	1006	5.313	7.907
#14	#43	1.693	43.0	2.25	1452	7.650	11.38
#18	#57	2.257	57.3	4.00	2581	13.60	20.24

FIGURE 13.19
American standard sizes of reinforcing bars based on inch-pound units. "Soft" metric conversions are also shown, although this form of designation is no longer favored.

Size Designation	Nominal Mass, kg/m	Nominal Dimensions	
		Diameter, mm	Cross-Sectional Area, mm²
10M	0.785	11.3	100
15M	1.570	16.0	200
20M	2.355	19.5	300
25M	3.925	25.2	500
30M	5.495	29.9	700
35M	7.850	35.7	1000
45M	11.775	43.7	1500
55M	19.625	56.4	2500

FIGURE 13.20
Hard metric reinforcing bar sizes, as produced in Canada. Actual bar dimensions result in convenient cross-sectional areas, while the nominal bar size corresponds with the bar diameter rounded to the nearest 5 millimeters.

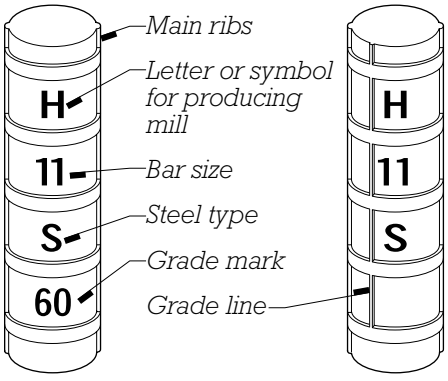
respectively. Grade 60 is generally the most economical and readily available of the four. ASTM A706 reinforcing bars are made with low-alloy steel that exhibits well-controlled ductility and is easily welded. They are used where concrete structures must meet demanding seismic design criteria or where extensive welding of reinforcing is required. In structures with especially heavy reinforcing requirements, reinforcing bars conforming to ASTM A1035, with strengths as high as 120,000 psi (830 MPa), may be used. With higher-strength bars, bar sizes may be reduced and the spacing between the bars increased in comparison to designs with lower-strength reinforcing. This reduces *rebar congestion*, making it easier to place and consolidate the concrete around the reinforcing (Figure 13.21).

Reinforcing bars in concrete structures that are exposed to salts, such as deicing salts or those in seawater, are prone to rust. Corrosion-resistant galvanized reinforcing bars and epoxy-coated reinforcing bars are often used in marine structures, highway structures, and parking garages for this reason. Stainless steel bars, zinc-and-polymer-coated bars, and special corrosion-resistant alloy bars are also sometimes used. Still in the experimental stage or newest to market are nonmetallic reinforcing bars made from high-strength fibers of carbon, aramid, or glass embedded in a polymeric matrix.

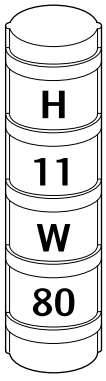
Welded Wire Reinforcement

As an alternative to conventional reinforcing bars, reinforcing is also produced in sheets or rolls of *welded wire reinforcement (WWR)*, also called *welded wire fabric (WWF)*, as a grid of wires or round bars spaced 2 to 12 inches (50 to 300 mm) apart (Figures 13.22 and 13.23). The lighter styles of *welded wire reinforcement* resemble cattle fencing and are used to provide light reinforcing for concrete slabs on grade and certain precast concrete elements. The heavier styles find use in concrete walls and structural slabs. Standard sheets range in size from 10 to 20 feet (3.1 to 6.1 m) in length and up to 8 feet (2.4 m) in width.

The size and spacing of the wires or bars, called the welded wire



#11 ASTM A615 Grade 60 Bar



#11 ASTM A706 Grade 80 Bar

FIGURE 13.21
Reinforcing bars are manufactured with identification marks, denoting the mill that produced the bars, bar size, and steel type and grade. Examples of steel types include S for ASTM A615 carbon steel, W for ASTM A706 low-alloy steel, and SS for ASTM A955 stainless steel. Steel grade is indicated either with a number, such as "60" for Grade 60 steel, or with short bars called grade lines, in which no bars indicates Grade 40 steel, one bar indicates Grade 60 steel, and two, three, or four bars indicate Grades 80, 100, and 120, respectively.

Wire Size and Type			
Smooth	Deformed	Nominal Diameter	Area
W20	D20	0.505 in. (12.8 mm)	0.200 in.^{2} (129 mm^2)
W16	D16	0.451 in. (11.5 mm)	0.160 in.^{2} (103 mm^2)
W14	D14	0.422 in. (10.7 mm)	0.140 in.^{2} (90.3 mm^2)
W12	D12	0.391 in. (9.3 mm)	0.120 in.^{2} (77.5 mm^2)
W10	D10	0.357 in. (9.1 mm)	0.100 in.^{2} (64.5 mm^2)
W8	D8	0.319 in. (8.1 mm)	0.080 in.^{2} (51.6 mm^2)
W6	D6	0.276 in. (7.0 mm)	0.060 in.^{2} (38.7 mm^2)
W4	D4	0.226 in. (5.7 mm)	0.040 in.^{2} (25.8 mm^2)
W2		0.160 in. (4.1 mm)	0.020 in.^{2} (12.9 mm^2)
W1.4		0.134 in. (3.4 mm)	0.014 in.^{2} (9.0 mm^2)

FIGURE 13.22
A partial listing of standard wires for welded wire reinforcement. The heaviest "wires" are more than ½ inch (12.7 mm) in diameter.

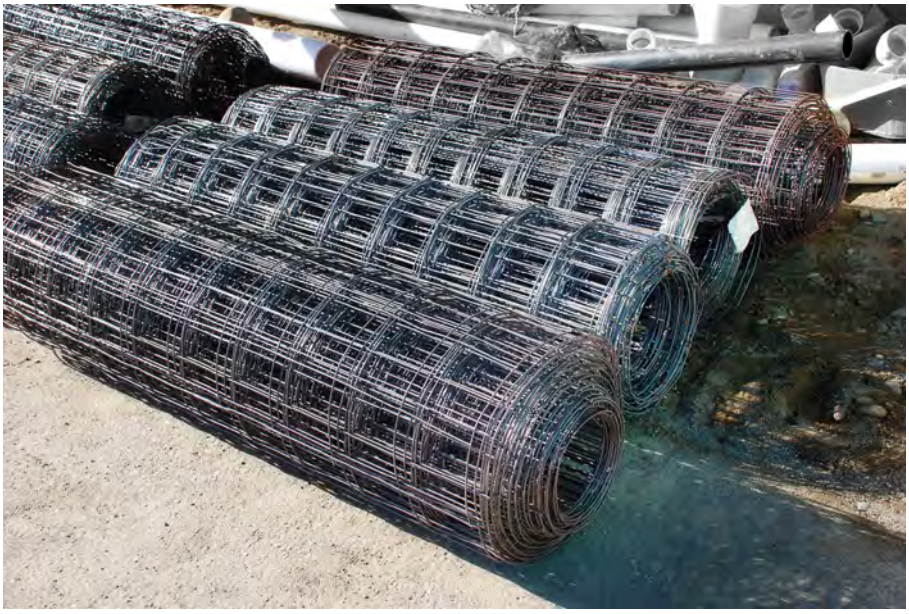


FIGURE 13.23
Rolls of welded wire reinforcement delivered to the construction site.
(Photo by Joseph Iano.)

reinforcement *style*, for a particular application are specified by first indicating the spacing of the wires and then the wire sizes and types. For example, the style designation 6 × 12–D12 × W5 indicates welded wire reinforcement with D12 longitudinal wires spaced at 6 inches (150 mm) and W5 transverse wires spaced at 12 inches (300 mm). D12 designates a deformed wire, 0.120 square inch (77.5 mm^2) in area. W5 designates a smooth wire, 0.050 square inch (32.3 mm^2) in area. Wires are available in different grades, or yield strengths. And for greater resistance to corrosion, wires may be epoxy coated, galvanized, or stainless steel.

The principal advantage of welded wire fabric over individual bars is economy of labor in placing the reinforcing, especially where a large number of small bars can be replaced by a single sheet of material.

Fabrication and Erection of Reinforcing Bars

The fabrication of reinforcing steel for a concrete construction project is analogous to the fabrication of steel shapes for a steel frame building (Chapter 11). The fabricator, working from engineering drawings, prepares shop drawings for the bars. After these drawings have been checked by the engineer or architect, the fabricator sets to work cutting the bar stock to length, making the necessary bends (Figure 13.24) and tying the fabricated bars into bundles that are tagged to indicate their destination in the building. The bundles are shipped to the building site, broken down, lifted by hand or hoisted by crane, and wired (or occasionally welded) together in the forms to await pouring of the concrete. The wire has a temporary function only, which is to hold the reinforcement in position until the concrete has set around them. Any transfer of load from one reinforcing bar to another in the completed structure is done by the concrete. Where two bars must be spliced, they are overlapped a specified number of bar diameters (typically 30), and the loads are transferred from one to the other by the surrounding concrete. The one common exception occurs in heavily reinforced columns where there is insufficient space to overlap the bars; there they are often spliced end-to-end rather than overlapped, and loads are transferred through welds or sleevelike mechanical splicing devices (Figure 13.25).

STANDARD HOOKS

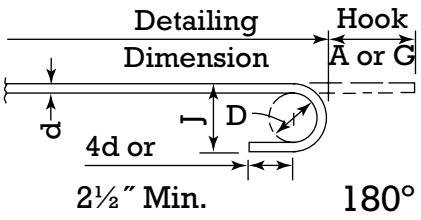
All specific sizes recommended by CRSI below meet minimum requirements of ACI 318

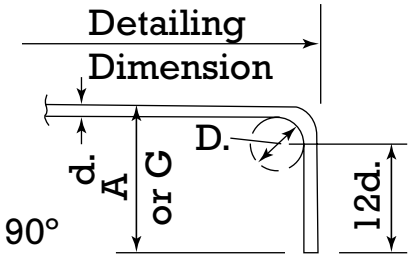
RECOMMENDED END HOOKS

All Grades

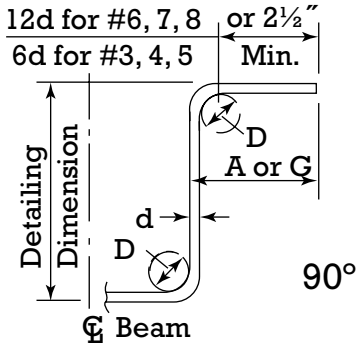
D=Finished bend diameter

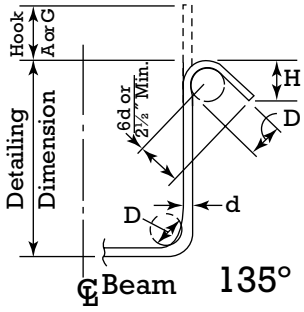
Bar Size	180° HOOKS			90° HOOKS
	D	A or G	J	A or G
# 3	2¼	5	3	6
# 4	3	6	4	8
# 5	3¾	7	5	10
# 6	4½	8	6	1-0
# 7	5¼	10	7	1-2
# 8	6	11	8	1-4
# 9	9½	1-3	11¾	1-7
# 10	10¾	1-5	1-1¼	1-10
# 11	12	1-7	1-2¾	2-0
# 14	18¼	2-3	1-9¾	2-7
# 18	24	3-0	2-4½	3-5



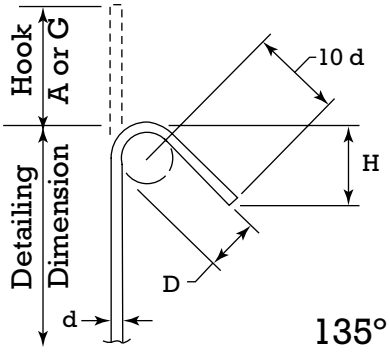


STIRRUP AND TIE HOOKS





135° SEISMIC STIRRUP/TIE HOOKS



STIRRUPS
(TIES SIMILAR)

STIRRUP AND TIE HOOK DIMENSIONS
Grades 40-50-60 ksi

Bar Size	D (in.)	90° Hook	135° Hook	
		Hook A or G	Hook A or G	H Approx.
#3	1¼	4	4	2½
#4	2	4½	4½	3
#5	2½	6	5½	3¾
#6	4½	1-0	7¾	4½
#7	5¼	1-2	9	5¼
#8	6	1-4	10¼	6

135° SEISMIC STIRRUP/TIE
HOOK DIMENSIONS
Grades 40-50-60 ksi

Bar Size	D (in.)	135° Hook	
		Hook A or G	H Approx.
#3	1½	5	3½
#4	2	6½	4½
#5	2½	8	5½
#6	4½	10¾	6½
#7	5¼	1-0½	7¾
#8	6	1-2¼	9

FIGURE 13.24

The bending of reinforcing bars is done according to precise standards in a fabricator's shop. *(Courtesy of Concrete Reinforcing Steel Institute.)*

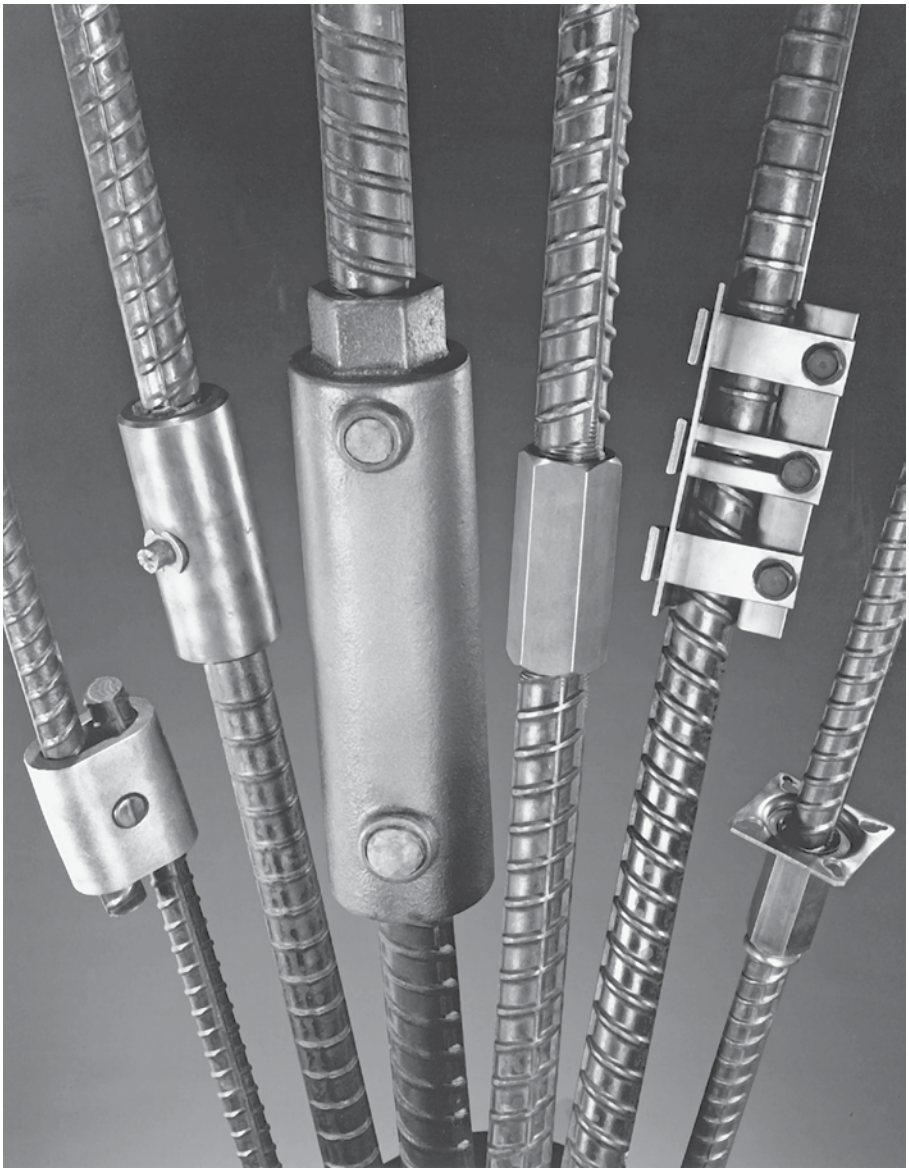


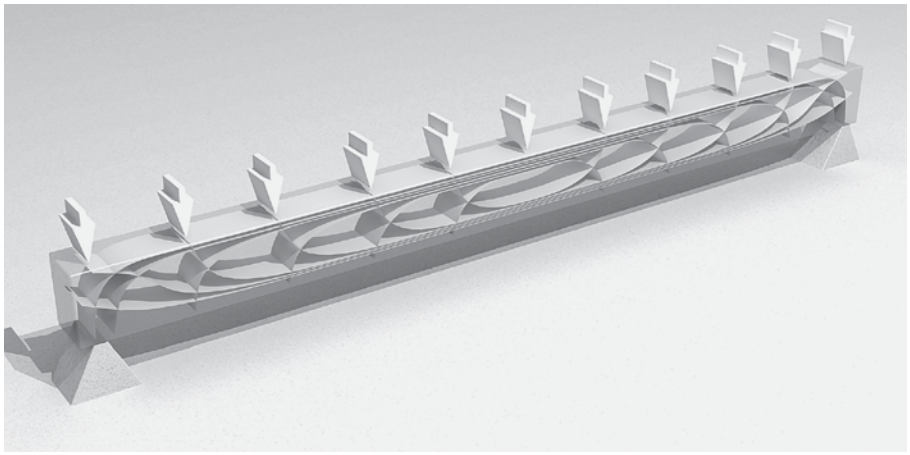
FIGURE 13.25
Some mechanical devices for splicing reinforcing bars. From left to right: A lapped, wedged connection, used primarily to connect new bars to old ones when adding to an existing structure. A welded connector, very strong and tough. A grouted sleeve connector for joining precast concrete components: One bar is threaded and screwed into a collar at one end of the sleeve, and the other bar is inserted into the remainder of the sleeve and held there with injected grout. A threaded sleeve, with both bars threaded and screwed into the ends of the sleeve. A simple clamping sleeve that serves to align compression bars in a column. A flanged coupler for splicing bars at the face of a concrete wall or beam: The coupler is screwed onto the threaded end of one bar, and its flange is nailed to the inside face of the formwork. After the formwork has been stripped, the other bar is threaded and screwed through a hole in the flange and into the coupler.
(Courtesy of ERICO, Inc.)

Reinforcing a Simple Concrete Beam

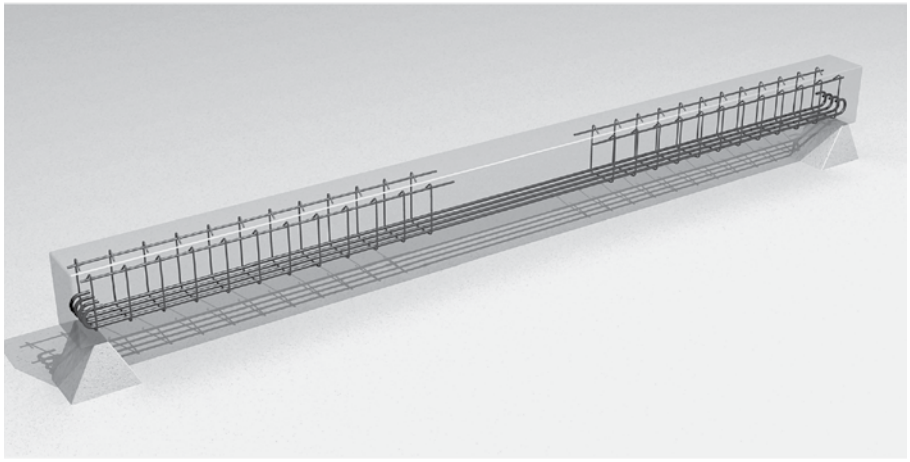
In an ideal, *simply supported beam* under uniform loading, compressive (squeezing) forces follow a set of archlike curves that create a maximum stress in the top of the beam at midspan, with progressively lower compressive stresses toward either end. A mirrored set of curves corresponds to paths of tensile (stretching) force, with stresses again reaching a maximum at the middle of the span (Figure 13.26). In an ideally reinforced concrete beam, steel reinforcing bars would be bent to follow these lines of tension, and the bunching of the bars at midspan would serve to resist the higher stresses at that point. It is difficult, however, to bend bars into these curves and to support the bars in such arrangements in the formwork, so a simpler rectilinear arrangement of reinforcing steel is substituted.

This arrangement consists of a set of bottom bars and stirrups. The *bottom bars* are placed horizontally near the bottom of the beam, leaving a specified amount of concrete below and to the sides of the rods as *cover* (Figure 13.27). The concrete cover provides a full embedment for the reinforcing bars and protects them from fire and corrosion. The bars are most heavily stressed at the midpoint of the beam span, with progressively smaller amounts of stress toward each of the supports. The differences in stress are dissipated from the bars into the concrete by means of *bond* forces, the adhesive forces between the concrete and the steel, aided by the ribs on the surface of the bars. At the ends of the beam, some stress remains in the steel, but there is no further length of concrete into which the stress can be dissipated. This problem is solved by bending the ends of the bars into *hooks*, which are semicircular bends of standard dimensions.

The bottom bars do the heavy tensile work in the beam, but some lesser tensile forces occur in a



(*a*)



(*b*)

FIGURE 13.26

(*a*) The directions of force in a simply supported beam (supported only at its ends) under uniform loading. The archlike lines represent compression, and the cablelike lines represent tension. Near the ends of the beam, the lines of strongest tensile force move upward diagonally through the beam. (*b*) Steel reinforcing for the same simply supported beam. The concrete resists compressive forces. The horizontal bars near the bottom of the beam resist the tensile forces. The vertical stirrups resist the lesser diagonal tensile forces near the ends of the beam. Note also that the combined action of concrete and steel in reinforced concrete elements is such that the reinforcing steel is usually loaded axially in tension or compression, and occasionally in shear, but never in bending. The bending stiffness of the reinforcing bars themselves is of no consequence in imparting strength to the concrete.

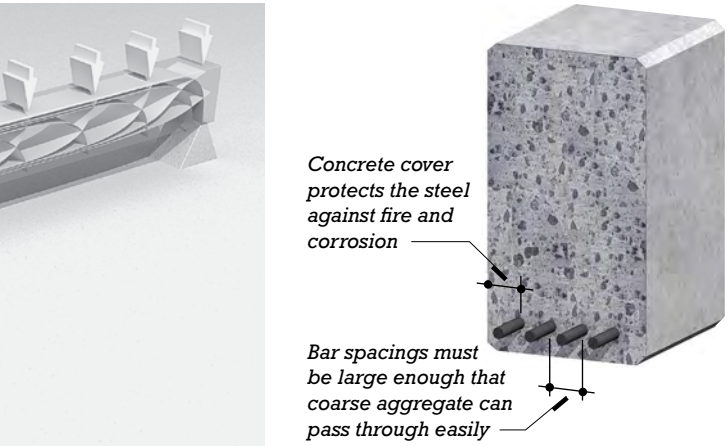


FIGURE 13.27

A cross section of a rectangular concrete beam showing cover and bar spacing.

diagonal orientation near the ends of the beam. These are resisted by a series of *stirrups*. The stirrups may be either open *U-stirrups*, as shown in Figure 13.26, or *closed stirrup-ties*, which are full rectangular loops of steel that wrap all the way around the longitudinal bars. U-stirrups are easier and less expensive to make and install and are sufficient for many situations, but stirrup-ties are required in beams that will be subjected to torsional (twisting) forces or to high compressive forces in the top or bottom bars. In either case, the stirrups furnish vertical tensile reinforcing to resist the cracking forces that run diagonally across them. A more efficient use of

FIGURE 13.28
A two-piece plastic bar support, called a "tower chair," supports a steel reinforcing bar for a structural concrete slab. To the left of the chair, a small concrete brick supporting a second bar in a position closer to the bottom of the slab is also partially visible. *(Photo by Joseph Iano.)*

steel would be to use diagonal stirrups oriented in the same direction as the diagonal tensile forces, but they would be more difficult to install.

When the simple beam of our example is formed, the bottom steel is supported at the correct cover height by *chairs* made of heavy steel wire or plastic (Figures 13.28 and 13.29). In a broad beam or slab, bars are supported by long chairs called *bolsters*. Chairs and bolsters remain in the concrete after pouring, even though their work is finished, because there is no way to get them out. In outdoor concrete work, the feet of the chairs and bolsters sometimes rust where they come in contact with the face of the beam or slab unless plastic or plastic-capped steel chairs are used. Where reinforced concrete is poured in direct contact with the soil, concrete bricks or small pieces of concrete may be used to support the bars instead of chairs, to avoid the possibility of rust forming under the feet of the metal chairs and spreading up into the reinforcing bars.

The stirrups in the simple beam that we have been examining are supported by wiring them to the bottom bars and by tying their tops to horizontal #3 top bars (the smallest standard size) that have no function in the beam other than to keep the stirrups upright and properly spaced until the concrete has been poured and cured.

Reinforcing a Continuous Concrete Beam

Most sitecast concrete beams are not of this simple type, because concrete lends itself most easily to one-piece structural frames with continuity from one beam span to the next. In a *continuous beam*, the bottom of the beam is in tension at midspan, and the top of the beam is in tension at points of support (such as at girders, columns, or walls). This means that top bars must be provided over the supports, and bottom bars in midspan, along with the usual stirrups, as illustrated in Figure 13.30.

Reinforcing Structural Concrete Slabs

A concrete slab that spans across parallel beams or walls (*one-way action*) is, in effect, a very wide beam. The reinforcing pattern for such a slab is similar to the reinforcing pattern in a beam, but with a larger number of smaller top and bottom bars distributed evenly across the width of the slab. Because the slab is wide, it has a large cross-sectional area of concrete that can usually resist the relatively weak diagonal tension forces near its supports without the aid of stirrups.

One-way slabs must be provided with *shrinkage–temperature steel*, a set of small-diameter reinforcing bars set at right angles to, and on top of, the primary reinforcing in the slab. Their function is to prevent cracks from forming parallel to the primary reinforcing because of concrete shrinkage, temperature-induced stresses, or miscellaneous forces that may occur in the building (Figure 13.31).

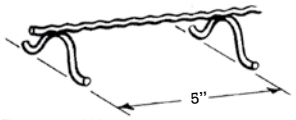
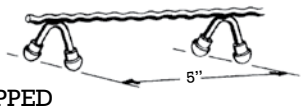
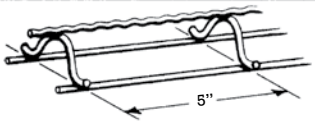
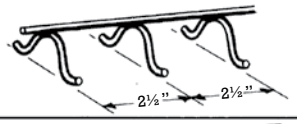
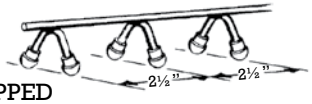
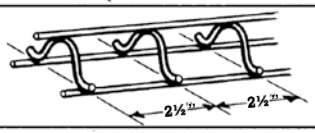
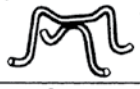
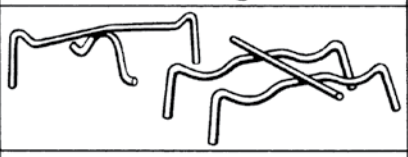
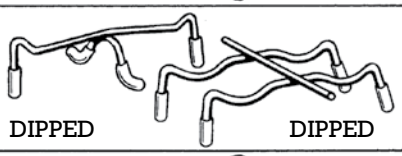
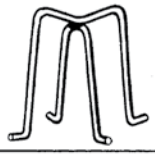
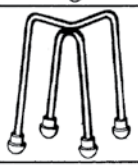
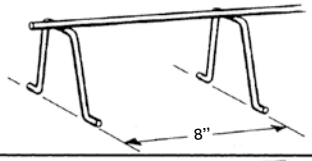
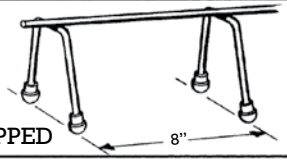
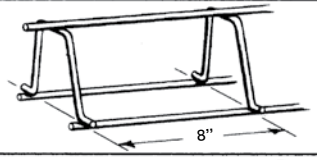
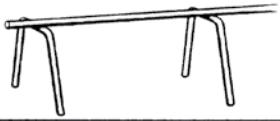
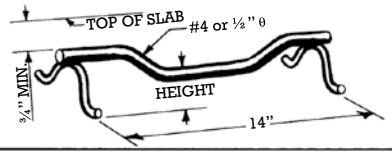
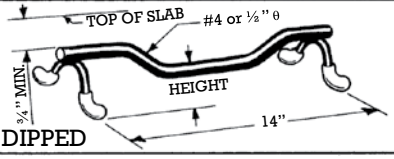
SYMBOL	BAR SUPPORT ILLUSTRATION	BAR SUPPORT ILLUSTRATION PLASTIC CAPPED OR DIPPED	TYPE OF SUPPORT	SIZES
SB		 CAPPED	Slab Bolster	¾, 1, 1½, and 2 inch heights in 5 ft. and 10 ft. lengths
SBU			Slab Bolster Upper	Same as SB
BB		 CAPPED	Beam Bolster	1, 1½, 2, over 2" to 5" heights in increments of ¼" in lengths of 5 ft.
BBU			Beam Bolster Upper	Same as BB
BC		DIPPED	Individual Bar Chair	¾, 1, 1½, and 1¾" heights
JC		 DIPPED DIPPED	Joist Chair	4, 5, and 6 inch widths and ¾, 1 and 1½ inch heights
HC		 CAPPED	Individual High Chair	2 to 15 inch heights in increments of ¼ inch
HCM			High Chair for Metal Deck	2 to 15 inch heights in increments of ¼ in.
CHC		 CAPPED	Continuous High Chair	Same as HC in 5 foot and 10 foot lengths
CHCU			Continuous High Chair Upper	Same as CHC
CHCM			Continuous High Chair for Metal Deck	Up to 5 inch heights in increments of ¼ in.
JCU		 DIPPED	Joist Chair Upper	14" span. Heights –1" thru + 3½" vary in ¼" increments

FIGURE 13.29

Chairs and bolsters for supporting reinforcing bars in beams and slabs. Bolsters and continuous chairs are made in long lengths for use in slabs. Chairs support only one or two bars each. *(Courtesy of Concrete Reinforcing Steel Institute.)*

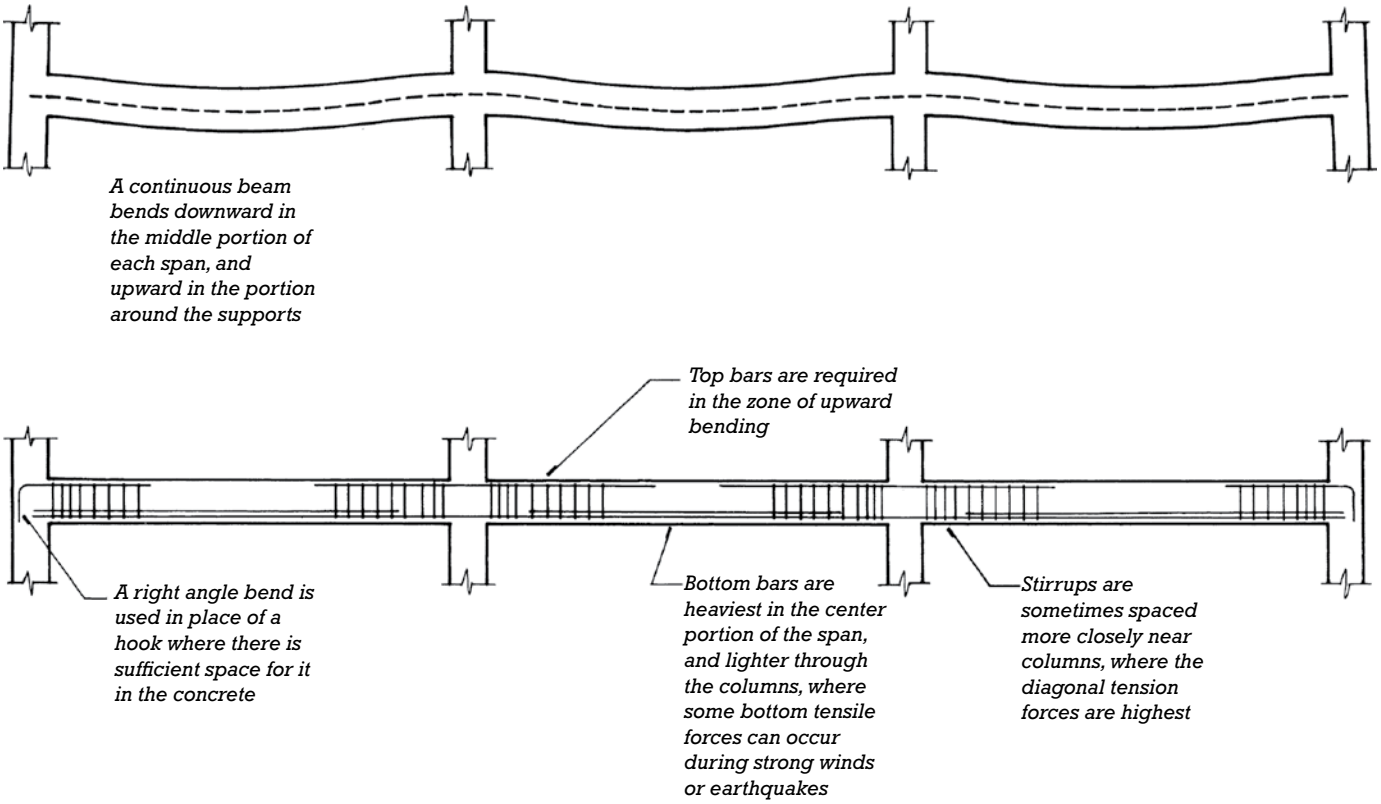


FIGURE 13.30

Reinforcing for a continuous beam that is supported across several spans. The upper diagram shows in exaggerated form the shape taken by a continuous beam under uniform loading; the broken line is the centerline of the beam. The lower diagram shows the arrangement of bottom steel, top steel, and stirrups conventionally used in this beam. The bottom bars are usually placed on the same level, but they are shown on two levels in this diagram to demonstrate the way in which some of the bottom steel is discontinued in the zones near the columns. There is a simple rule of thumb for determining where the bending steel must be placed in a beam: Draw an exaggerated diagram of the shape the beam will take under load, as in the top drawing of this illustration, and put the bars as close as possible to the convex edges.

Two-Way Slab Action

A structural economy mostly unique to concrete frames is realized through the use of *two-way action* in floor and roof slabs. Two-way slabs, which work best for bays that are square or nearly square, are reinforced equally in both directions and share the bending forces equally between the two directions. In comparison to equivalent one-way slabs, two-way slabs can be somewhat shallower, use less reinforcing steel, and cost less. Figure 13.32 illustrates the concept of two-way action. Several different two-way concrete framing systems will be shown in detail in Chapter 14.

The country . . . near Taliesin, my home and workshop, is the bed of an ancient glacier drift. Vast busy gravel pits abound there, exposing heaps of yellow aggregate once and still everywhere near, sleeping beneath the green fields. Great heaps, clean and golden, are always waiting there in the sun. And I never pass . . . without an emotion, a vision of the long dust-whitened stretches of the cement mills grinding to impalpable fineness the magic powder that would "set" my vision all to shape; I wish both mill and gravel endlessly subject to my will . . . . Materials! What a resource.

—Frank Lloyd Wright, in *Architectural Record*, October 1928

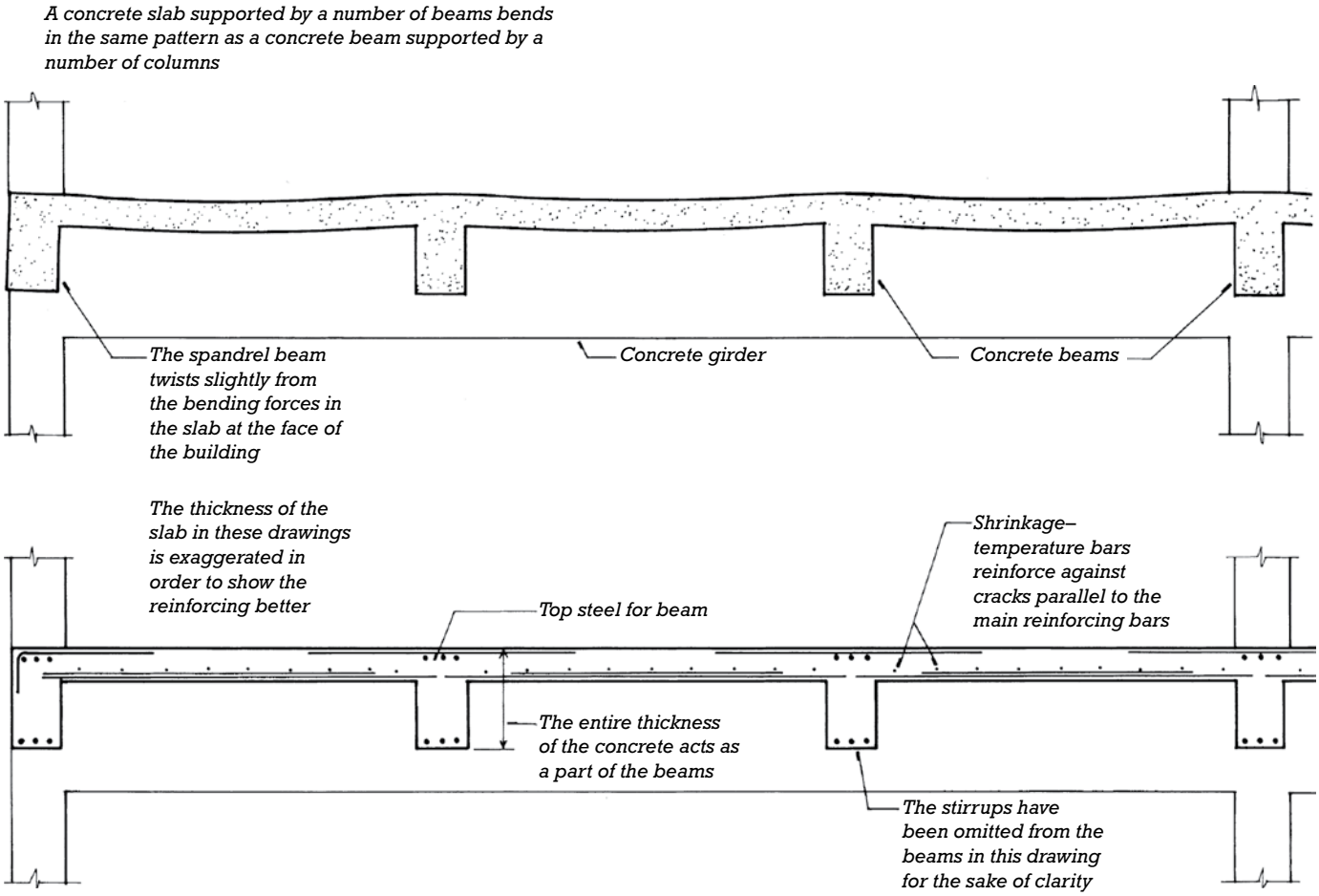


FIGURE 13.31

Reinforcing for a one-way concrete slab. The reinforcing is similar to that for a continuous beam, except that stirrups are not usually required in the slab, and shrinkage–temperature bars must be added in the perpendicular direction. The slab does not sit on the beams; rather, the concrete around the top of a beam is part of both the beam and the slab. A concrete beam in this situation is considered to be a T-shaped member, with a portion of the slab acting together with the stem of the beam, resulting in greater structural efficiency and reduced beam depth.

Interactive Exercise

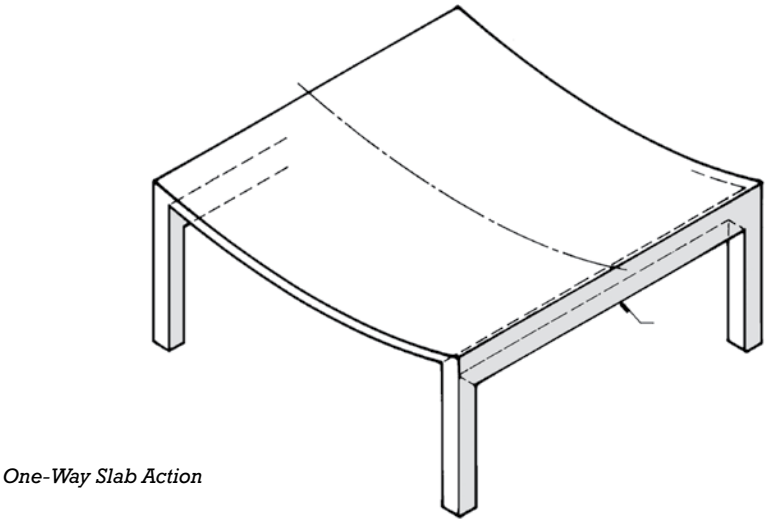
Reinforcing Concrete Columns

Columns contain two types of reinforcing: *Vertical bars* (also called *column bars*) are large-diameter bars that share the compressive loads with the concrete, resist tensile stresses that may occur in columns, and impart ductility to the column (important for resistance to earthquake forces). *Ties* of small-diameter steel bars wrapped around the vertical bars help to prevent them from buckling under load: Inward buckling is prevented by the concrete core of the column and outward buckling by the ties (Figure 13.33). The vertical bars may be arranged in either circular or rectangular patterns. The ties may be either of two types: column spirals or column ties.

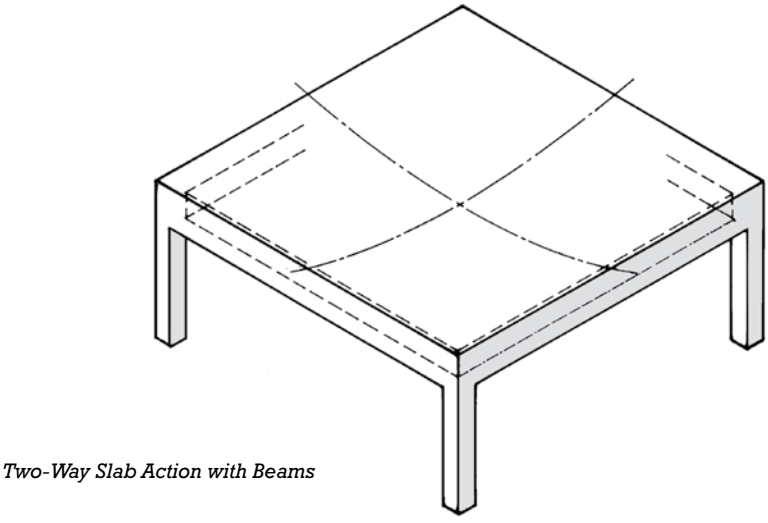
Column spirals are shipped to the construction site as tight coils of rod that are expanded accordion fashion to the required spacing and wired to the vertical bars. The vertical bars must be in a circular (or four-square) arrangement so as to make contact with the spiral. The outer form of the column, though, can be circular or rectangular. By overlapping spirals, even long lines of vertical bars in a reinforced wall can be tied with spirals.

Column ties are discrete, closely spaced hoops, individually wired in place. They are used mostly to tie rectangular arrangements of vertical bars. A single column tie can effectively restrain four vertical bars, one at each bent corner of the tie. For columns with more than four bars, additional ties are added to provide restraint for the bars between corners (Figure 13.34).

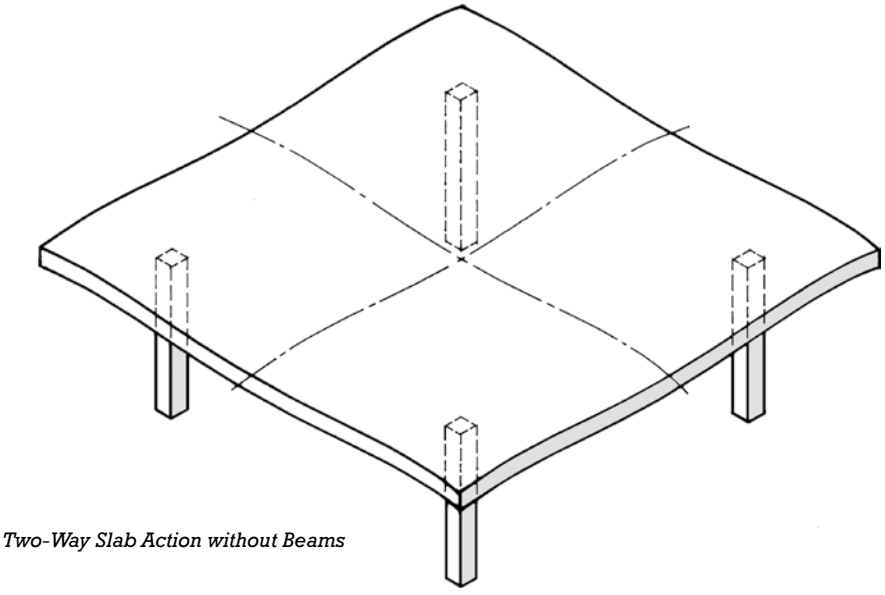
A circular arrangement of vertical bars is often more economical than a rectangular one because it avoids the need for added ties to capture bars between corners. However, column



One-Way Slab Action



Two-Way Slab Action with Beams



Two-Way Slab Action without Beams

FIGURE 13.32
One-way and two-way slab action, with deflections greatly exaggerated.

ties are generally more economical than spirals, so even columns with circular bar arrangements may be tied with discrete, circular ties. However, spiral-tied columns are more effective at resisting dynamic loads, such as occur during earthquakes. To minimize labor costs, column reinforcing may be wired together while lying on the ground, and the finished column cage lifted into final position by crane (Figure 13.35). Or, column cages may be assembled in the reinforcing fabricator's shop and delivered ready for installation to the construction site (Figure 13.34).

Fibrous Reinforcing

Fibrous reinforcing is composed of short fibers of glass, steel, or polypropylene, ¾ to 2½ inches (19 to 64 mm) in length, that are added to the concrete mix. *Microfiber reinforcing* is added in relatively low dosages and is intended to reduce *plastic shrinkage cracking*, which frequently occurs while the concrete is still in a plastic state, during the earliest stages of curing. Microfiber reinforcing makes little if any contribution to the mechanical properties of the hardened concrete. *Macrofiber reinforcing*, usually of polypropylene or steel-polypropylene blend, also resists long-term cracking due to drying shrinkage and thermal stresses. Macrofiber reinforcing is thicker in diameter than microfiber reinforcing and is added to concrete at dosages roughly five times greater. In some cases, macrofiber reinforcing fully replaces the usual shrinkage–temperature steel in concrete slabs. It can also improve concrete's resistance to impact, abrasion, and shock. Glass fibers are also added to concrete to produce glass-fiber-reinforced concrete (GFRC), used, for example, in the manufacture of lightweight concrete cladding panels (see Chapter 20).

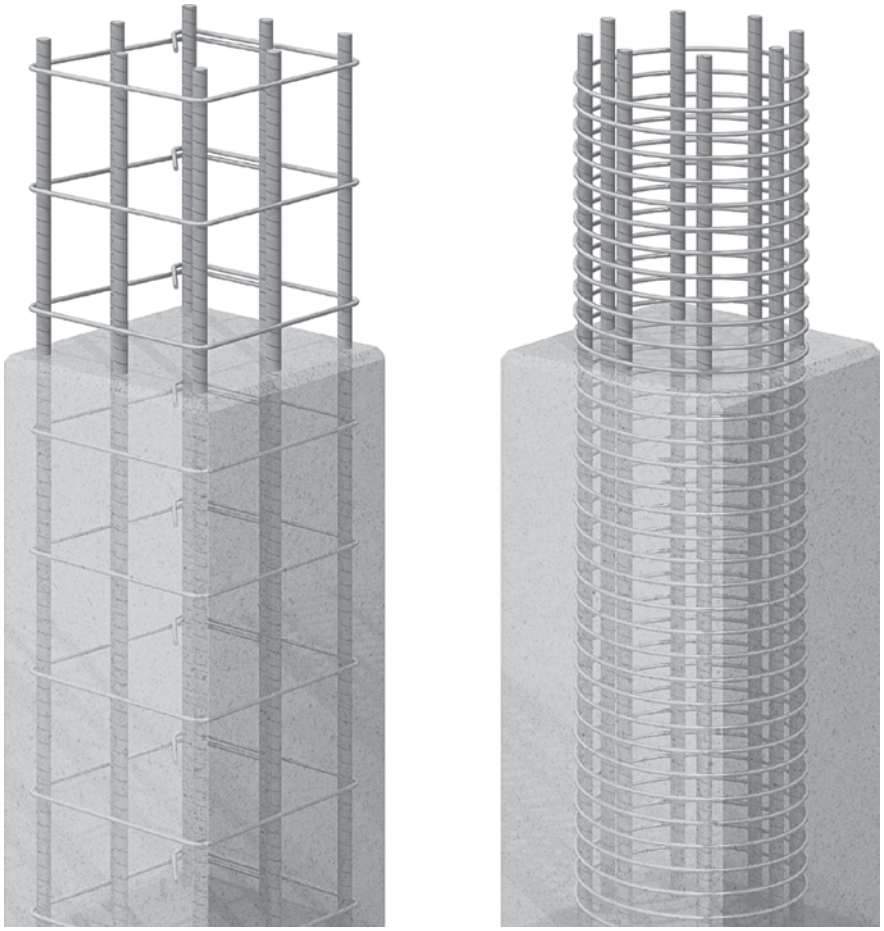


Figure 13.33
Reinforcing for concrete columns. To the left is a column with a rectangular arrangement of vertical bars and column ties. To the right is a circular arrangement of vertical bars with a column spiral. Regardless of the bar and tie arrangements, the outer form of the column can be cast round or square.

Interactive Exercise

Figure 13.34
Rectangular column cages, fabricated offsite, arrive on the construction site on a flatbed trailer. The vertical bars are tied with column ties. Note the added ties used to capture bars between corners. Each cage is tagged to identify its intended location in the building frame. *(Photo by Joseph Iano.)*

FIGURE 13.35
A large reinforcing cage being assembled while resting on its side. Once complete, it will be lifted into final position, where it will form part of the central core structure of a tall building. Note the large rectangular ties. The worker standing on top of the reinforcing cage is installing shorter ties between pairs of column bars. Additional ties are stacked toward the back, right-hand side of the top of the cage *(Photo by Joseph Iano.)*

Concrete Creep

In addition to plastic and drying shrinkage, concrete is subject to long-term *creep*. When placed under sustained compressive stress from its own weight, the weight of other permanent building components, or the force of prestressing (as described later in this chapter), concrete will gradually and permanently shorten over a period of months or years. In some circumstances, this dimensional change is of sufficient magnitude that it must be accounted for in the design and detailing of other parts. For example, when a brick veneer cladding system is supported on a concrete building frame, the shrinkage of the concrete combined with other factors affecting movement of the masonry require that horizontal movement joints be designed into the cladding system to accommodate the differential movement between the cladding and the supporting structure. If these joints are not provided, or if they are too narrow and unable to accommodate the extent of movement, the cladding system can fail as it becomes compressed, in part, by the shortening of the concrete structure. As a rule of thumb, site-cast concrete building frames can be expected to shorten in height under the influence of their own weight and other dead loads at the rate of 1/16 inch for every 10 feet (½ mm per meter) of building height.

Prestressing

When a beam supports a load, the compression side of the beam is squeezed slightly and the tension side is stretched. In a reinforced concrete beam, the stretching tendency is resisted by the reinforcing steel but not by the concrete. When the steel elongates under tension, the concrete around it forms cracks that run from the edge of the beam to the horizontal plane in the beam, above which compressive forces occur. This cracking is even visible to the unaided eye in reinforced concrete beams that are loaded to (or beyond) their full capacity. In effect, more than half of the concrete in the beam is doing no useful work except to hold the steel in position and protect it from fire and corrosion (Figure 13.36, *top*).

If the reinforcing bars could be stretched to a high tension before the beam is loaded and then released against the concrete that surrounds them, they would place the concrete in compression. If a load were subsequently put on the beam, the tension in the stretched steel would increase further, and the compression in the concrete surrounding the steel would diminish. If the initial tension, or *prestress*, in the steel bars were of sufficient magnitude, however, the surrounding concrete would never be subjected to tension, and no cracking would occur. Furthermore, the beam would be capable of carrying a greater load with the same amounts of concrete and steel than if it were merely reinforced in the conventional manner. This is the rationale for *prestressed concrete*. Prestressed members, particularly those designed to work in bending, contain less concrete than reinforced members of equivalent strength. Their lighter weight also pays off by making precast, prestressed concrete members easier and cheaper to transport. For this reason, structural precast concrete used for slabs, beams, and girders (and in some cases columns as well) is usually prestressed.

In practice, ordinary reinforcing bars are not sufficiently strong to serve as prestressing steel. Prestressing is practical only with very high-strength steel strands that are manufactured for the purpose. These are made of cold-drawn steel wires that are formed into small-diameter cables.

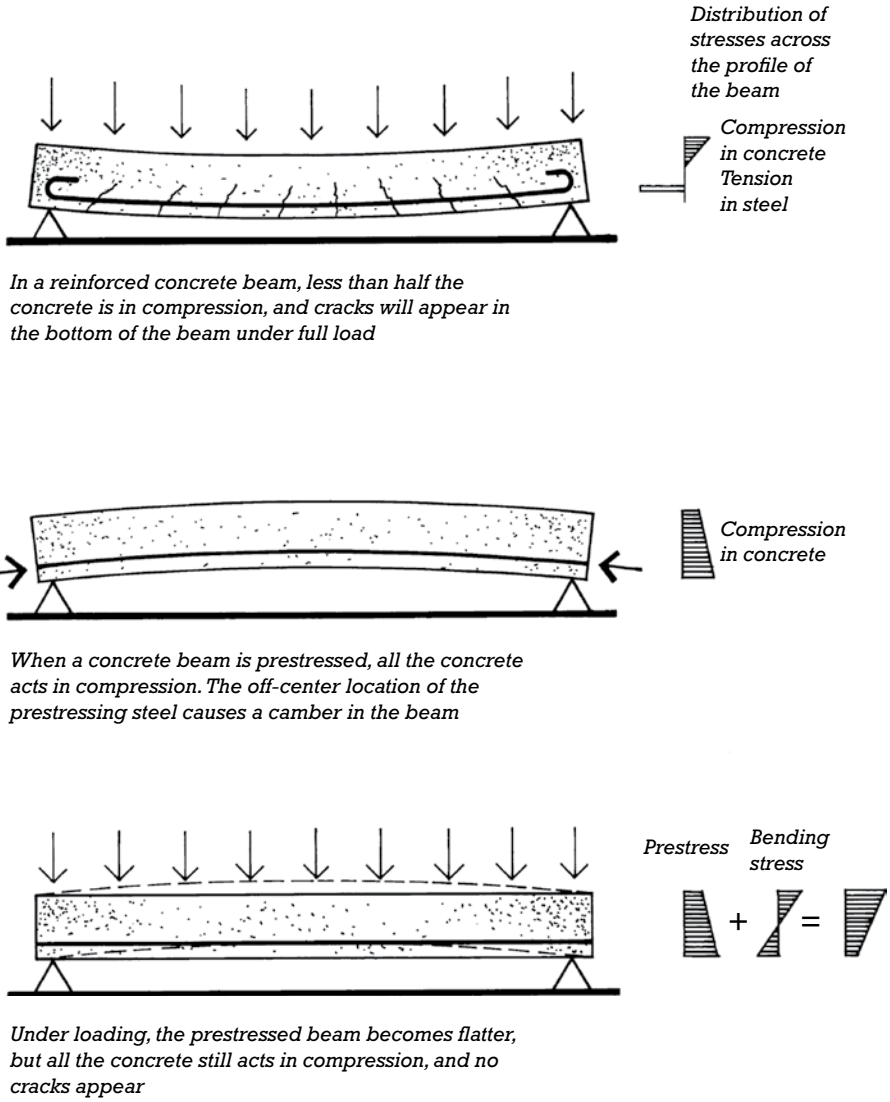


FIGURE 13.36
The rationale for prestressing concrete. In addition to the elimination of cracks in the prestressed beam, the structural action is more efficient than that of a reinforced beam. Therefore, the prestressed beam uses less material. The small diagrams to the right indicate the distribution of stresses across the vertical cross section of each of the beams at midspan.

Pretensioning

Prestressing is accomplished in two different ways. *Pretensioning* is used with precast concrete members: High-strength steel strands are stretched tightly between abutments in a precasting plant before the concrete is cast. The concrete member (or, more commonly, a series of concrete members arranged end-to-end) is then cast around the stretched steel. The curing concrete adheres to the strands along their entire length. After the concrete has cured to a specified minimum compressive strength, the strands are cut off at either end of each member. This releases the external tension on the steel, allowing it to recoil slightly, which squeezes all of the concrete of the member into compression. If, as is usually the case, the steel is placed as close as possible to the tension side of the member, the member takes on a decided *camber* (lengthwise arching) at the time the steel strands are cut (Figure 13.37). Much or all of this camber disappears later when the member is subjected to loads in a building.

The strong abutments needed to hold the tensioned strands prior to the pouring of concrete are very expensive to construct except in a single fixed location where many concrete members can be created within the same set of abutments. For this reason, pretensioning is useful only for concrete members cast in precasting plants.

Posttensioning

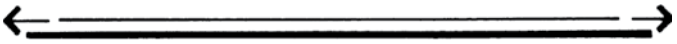
Unlike pretensioning, *posttensioning* is done almost exclusively in place on the building site. High-strength steel strands (called *tendons*) are covered with a steel or plastic tube to prevent them from bonding to the concrete and are not tensioned until the concrete is poured and has achieved adequate strength. Each tendon is anchored to a steel plate embedded

in one end of the beam or slab. A hydraulic jack is inserted between the other end of the tendon and a similar steel plate in the other end of the member. The jack applies a large tensile force to the tendon while compressing the concrete with an equal but opposite force that is applied through the plate. The stretched tendon is anchored to the plate at the second end of the member before the jack is removed (Figures 13.38, 13.39, and 13.40). For very long members, the tendons are jacked from both ends to be sure that frictional losses in the tubes do not prevent uniform tensioning.

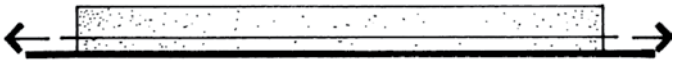
The net effect of posttensioning is the same as that of pretensioning. The difference is that in posttensioning, abutments are not needed because the concrete member itself provides the opposing force needed to tension the steel. When the posttensioning process is complete, the tendons may be left unbonded, or, if they are in a steel tube, they may be bonded by injecting grout to fill the space between the tendons and the tube. Bonded construction is common in bridges and other heavy structures, but most posttensioning in buildings is done with unbonded tendons. These are made up of cold-drawn steel wires and are roughly ½ inch (13 mm) in diameter (Figure 13.41). The tendon is coated with a lubricant and covered with a plastic sheath at the factory.

Even higher structural efficiencies are possible in a prestressed beam or slab if the steel strands are placed to follow as closely as possible the lines of tensile force that are diagrammed in Figure 13.26. In a posttensioned beam or slab, this is done by using chairs of varying heights to support the tendons along a curving line that closely follows the center of the tensile forces in the member. Such a tendon is referred to as being *draped* (Figure 13.42). Draping is impractical in pretensioned members because the tendons would have to be pulled down at many points along their length. But pretensioned strands can be *harped*, that is, pulled up and down in the formwork to make a downward-pointing or flattened V shape in each member that approximates very roughly the shape of a draped tendon (Figure 13.43).

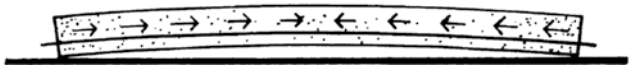
Because it is always highly compressed by prestressing force, the concrete in a prestressed member is subject to creep. The steel strands also stretch slightly over time and lose some of their prestressing force. Initial prestressing forces must be increased slightly above their optimal values to make up for these long-term changes. Further increases in initial tension are needed to accommodate the slight curing shrinkage that takes place in concrete, small, short-term movements caused by elastic shortening of the concrete during structural loading, and frictional losses and initial slippage or set of the strand anchors in posttensioned members.



1. The first step in pretensioning is to stretch the steel prestressing strands tightly across the casting bed.



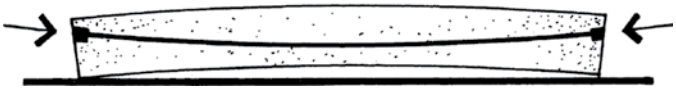
2. Concrete is cast around the stretched strands and cured. The concrete bonds to the strands.



3. When the strands are cut the concrete goes into compression and the beam takes on a camber

FIGURE 13.37
Pretensioning. Photographs of pretensioned steel strands for a beam are shown in Chapter 15.

1. In posttensioning, the concrete is not allowed to bond to the steel strands during curing.



2. After the concrete has cured, the strands are tensioned with a hydraulic jack and anchored to the ends of the beam. If the strands are draped, as shown here, higher structural efficiency is possible than with straight strands.

FIGURE 13.38
Posttensioning, using draped strands to more nearly approximate the flow path of tensile forces in the beam.

FIGURE 13.39
Posttensioning draped tendons in a large concrete beam with a hydraulic jack. Each tendon consists of a number of individual high-strength steel strands. The bent bars projecting from the top of the beam will be embedded in the concrete slab that the beam will support to allow them to act together as a composite structure. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

FIGURE 13.40
Most beams and slabs in buildings are posttensioned with plastic-sheathed, unbonded tendons. The pump and hydraulic jack (also called a ram) are small and portable. *(Courtesy of Constructive Services, Inc., Dedham, MA.)*

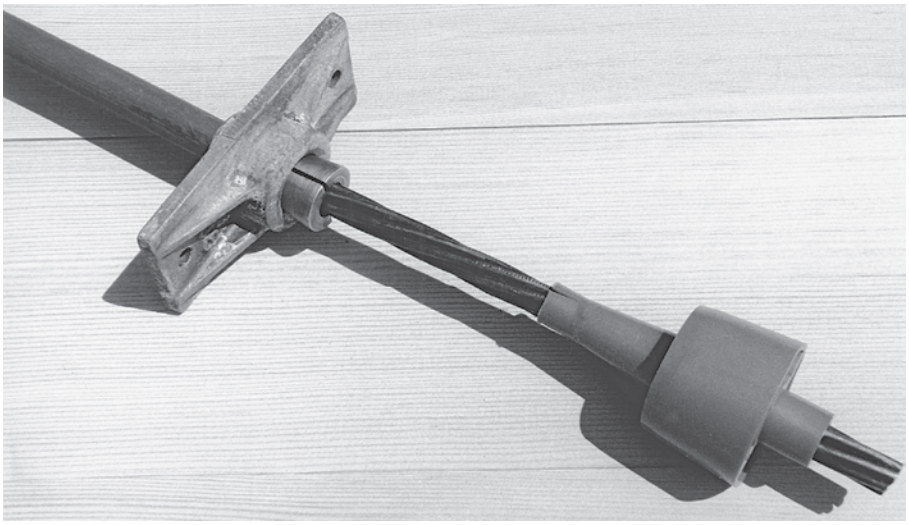
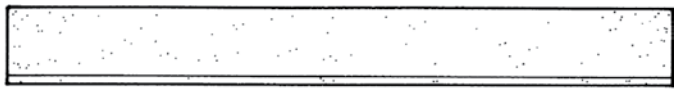


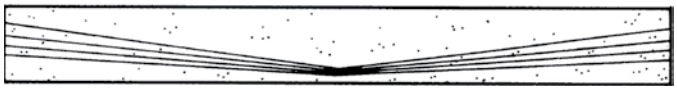
FIGURE 13.41
End anchorage for a posttensioning tendon. The steel anchor plate and plastic pocket former are cast into the edge of the concrete slab. After the concrete has cured, the formwork and pocket former are removed, exposing the anchor plate. The two conical wedges are inserted around the tendon and into the hole in the anchor plate. The ram presses against the wedges and draws the tendon through until the gauge on the pump indicates that the required tension has been reached. When the ram is withdrawn, the wedges are drawn into the conical hole, grip the tendon, and maintain the tension. After all the tendons have been tensioned, the excess lengths of tendon are cut off and the pockets grouted flush with the edge of the slab. *(Photo by Edward Allen.)*

FIGURE 13.42
Draped posttensioning tendons. As explained in Chapter 14, banded tendons run from lower left to upper right and distributed tendons run in the perpendicular orientation. *(Photo by Joseph Iano.)*



Straight pretensioning strands

Depressed pretensioning strands



Harped pretensioning strands

FIGURE 13.43
Shaping pretensioning strands to improve structural efficiency. Examples of depressed and harped strands are shown in Chapter 15.

CONCRETE STANDARDS

Among the major structural materials, concrete is unique in that the largest share of it is manufactured in-place on the construction site rather than in a factory. A great range of ingredients from diverse sources may be used in concrete manufacture, there is broad latitude in concrete formulation, and the environmental conditions under which concrete is made vary with locale, season, and day-to-day weather. In the finished product, a wide range of strengths, durability, fire resistance, and other properties can be achieved.

In the United States, two standards establish basic quality requirements for concrete building structures. ACI 318 Building Code Requirements for Concrete Structures sets minimum regulatory requirements for concrete buildings. The related ACI 301 Specifications for Structural Concrete for Buildings translates these requirements into a form appropriate for construction documents. Together, these documents address every aspect of concrete work: formwork, reinforcement, chairs and bolsters, concrete mixtures, handling and placing of concrete, lightweight concrete, prestressing, and the use of concrete in exposed architectural surfaces. They function as the common basis for everyone who works in designing and constructing concrete buildings of all types.

INNOVATIONS IN CONCRETE

Of all the major structural building materials, concrete seems the most subject to continual innovation in its formulation and capabilities. Some such improvements to ordinary concrete have already been discussed in this chapter, such as the use of supplementary cementitious materials and other admixtures to modify concrete properties, high compressive strength concrete mixtures, self-consolidating concrete, and fibrous reinforcing.

One major area of continuing development is in the improvement of concrete strength and ductility properties. *Engineered cementitious composites* (*ECCs*) are precisely tailored mixtures of polymer fiber-reinforcing, cementitious materials, and fine aggregate that produce concretes with higher tensile strength and ductility. ECCs exhibits stress–strain behavior not unlike ductile metals, resulting in materials with improved durability under flexural and seismic loads.

Ultra-high-performance concretes can, with careful mix design, achieve compressive strengths as high as 30,000 psi (200 MPa). They are formulated from portland cement, silica fume, silica or quartz flour (extremely finely ground silica or quartz), fine sand, high-range water reducer, water, and steel fibrous reinforcing. The resulting concrete is stronger, less permeable, and more durable than conventional high-strength mixes. Added steel macrofiber reinforcing imparts tensile strength and ductility (Figures 13.44 and 13.45). Or, with the addition of densely arrayed fine steel mats, called *micro-reinforcement*, concrete that is very mechanically tough and with even higher tensile strength and ductility can be produced.

Pervious concrete is made with gap- or uniformly graded aggregate so that

FIGURE 13.44
The Shawnessy LRT Station in Calgary, Alberta, designed by Stantec Architecture, Ltd. The canopy shells were cast from ultra-high performance concrete and are only ¾ inch (19 mm) thick. *(Photo by Tucker Photography, courtesy of Lafarge North America, Inc.)*

FIGURE 13.45
Casting of a concrete shell for the Shawnessy LRT Station shown in Figure 13.44. The shells were injection-molded, a technique in which the concrete is cast in a fully enclosed mold rather than in a conventional open-sided form. In this photograph, the two halves of the mold have been separated and the shell is being lifted with the aid of a temporary frame. *(Photo by Tucker Photography, courtesy of Lafarge North America, Inc.)*

15 to 30 percent of the finished concrete consists of open voids. Pervious concrete paving allows rainwater to pass directly through the paving into the soil below, rather than flow across its surface. Pervious paving reduces water volumes directed to municipal stormwater systems and lessens the contamination of nearby bodies of water by surface runoff carrying oils and other contaminants.

Light-transmitting concrete is made from precast concrete blocks or panels with embedded optic fibers or fabrics that allow light to pass through while retaining the strength and durability of the concrete. It finds application in nonstructural partitions, countertops, and other architectural elements.

Reportedly in development are *self-healing concrete*, which better protects steel reinforcing from corrosion and improves concrete durability, and concrete with irradiated, recycled plastic aggregate, that improves concrete strength and makes productive use of plastic waste.

CSI/CSC MasterFormat Sections for Concrete Construction

03 11 00	**CONCRETE FORMING**
03 21 00	**REINFORCEMENT BARS**
03 21 11	Plain Steel Reinforcement Bars
03 21 13	Galvanized Steel Reinforcement Bars
03 21 16	Epoxy-Coated Steel Reinforcement Bars
03 21 19	Stainless Steel Reinforcement Bars
03 21 21	Composite Reinforcement Bars
02 22 00	**FABRIC AND GRID REINFORCING**
03 23 00	**STRESSED TENDON REINFORCING**
03 24 00	**FIBROUS REINFORING**
03 31 00	**STRUCTURAL CONCRETE**
03 31 16	Lightweight Structural Concrete
03 31 19	Shrinkage-Compensating Structural Concrete
03 31 23	High-Performance Structural Concrete
03 31 24	Ultra High-Performance Structural Concrete
03 38 00	**POST-TENSIONED CONCRETE**

Key Terms

portland cement
concrete
aggregate
coarse aggregate
fine aggregate
curing
hydration
heat of hydration
drying shrinkage
clinker
air-entraining cement
white portland cement
lightweight aggregate
structural lightweight aggregate
expanded shale aggregate
vermiculite
perlite
water
supplementary cementitious material (SCM)
pozzolan
fly ash
silica fume, microsilica
natural pozzolan
high-reactivity metakaolin
blast furnace slag, slag cement
hydraulic cement
blended hydraulic cement
(concrete) admixture
air-entraining admixture
water-reducing admixture
high-range water-reducing admixture, superplasticizer
accelerating admixture
retarding admixture
workability agent
shrinkage-reducing admixture
corrosion inhibitor
freeze protection admixture
extended set-control admixture
coloring agent
high performance concrete (HPC)

ultra-high performance concrete (UHPC)
water–cement ratio, w-c ratio
transit-mixed concrete
slump test
slurry
segregation
dropchute
consolidation
self-consolidating concrete (SCC)
formwork
form release compound
precasting
sitecasting, cast-in-place construction
reinforced concrete
steel reinforcing bar (rebar)
deformed reinforcing bar
rebar congestion
welded wire reinforcement (WWR), welded wire fabric (WWF)
(welded wire reinforcement) style
simply supported beam
bottom bar
cover
bond
hook
stirrup
U-stirrup
closed stirrup-tie
chair
bolster
continuous beam
one-way action
shrinkage–temperature steel
two-way action
vertical bar, column bar
tie
column spiral
column tie
fibrous reinforcing
microfiber reinforcing
plastic shrinkage cracking
macrofiber reinforcing
creep
prestress
prestressed concrete
pretensioning
camber
posttensioning
tendon
draped tendon
harped tendon
engineered cementitious composite (ECC)
micro-reinforcement
pervious concrete
light-transmitting concrete
self-healing concrete

Review Questions

1. What is the difference between cement and concrete?

2. List the conditions that must be met to make a satisfactory concrete mix.

3. List the precautions that should be taken to cure concrete properly. How do these change in very hot, very windy, and very cold weather?

4. What problems are likely to occur if concrete has too low a slump? Too high a slump? How can the slump be increased without increasing the water content of the concrete mixture?

5. Explain how steel reinforcing bars work in concrete.

6. Explain the role of stirrups in beams.

7. Explain the role of ties in columns.

8. What does shrinkage–temperature steel do? Where is it used?

9. Explain the differences between reinforcing and prestressing and the relative advantages and disadvantages of each.

10. Under what circumstances would you use pretensioning, and under what circumstances would you use posttensioning?

11. Explain the advantages of using higher-strength reinforcing bars in concrete that requires very heavy reinforcing.

Exercises

1. Design a simple concrete mixture. Mix it and pour some test cylinders for several water–cement ratios. Cure and test the cylinders. Plot a graph of concrete strength versus water–cement ratio.

2. Sketch from memory the pattern of reinforcing for a continuous concrete beam. Add notes to explain the function of each feature of the reinforcing.

3. Design, form, reinforce, and cast a small concrete beam, perhaps 6 to 12 feet (2 to 4 m) long. Get help from a teacher or professional, if necessary, in designing the beam.

4. Visit a construction site where concrete work is being done. Examine the forms, reinforcing, and concrete work. Observe how concrete is brought to the site, transported, placed, compacted, and finished. How is the concrete supported after it has been poured? For how long?

Selected References

American Concrete Institute. *Manual of Standard Practice*. Schaumburg, IL, updated regularly.

A compendium of standards for all aspects of reinforced concrete design, mixing, pouring, curing, finishing, and maintenance. Includes ACI 301.

Concrete Reinforcing Steel Institute. *Manual of Standard Practice*. Schaumburg, IL, updated regularly.

Specifications for reinforcing, steel, welded wire fabric, bar supports, detailing, fabrication, and installation are standardized in this booklet.

Mehta, P. Kumar, and J. M. Monteiro Paulo. *Concrete: Microstructure, Properties, and Materials* (4th ed.). New York, McGraw-Hill, 2014.

For the reader who wishes to explore further the science and mechanics of concrete, this text provides an in-depth treatment of concrete materials, formulation, and behavior.

Portland Cement Association. *Design and Control of Concrete Mixtures*. Skokie, IL, Author, updated regularly.

This book summarizes clearly and succinctly, with many explanatory photographs and tables, the state of current practice in making, placing, finishing, and curing concrete.

Websites

American Concrete Institute (ACI): www.concrete.org

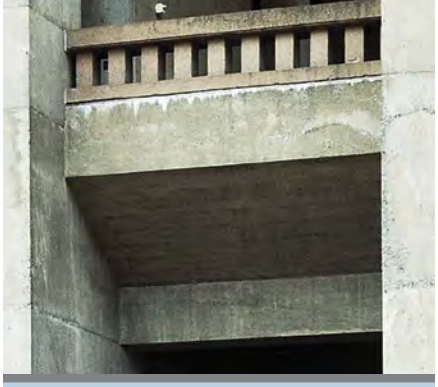
Carbon Upcycling UCLA: www.co2concrete.com

Concrete Reinforcing Steel Institute (CRSI): www.crsi.org

Concrete Sustainability Council: www.concretesustainabilitycouncil.org

Concrete Sustainability Hub: cshub.mit.edu

Portland Cement Association (PCA): www.cement.org



14

Sitecast Concrete Framing Systems

- **Casting a Concrete Slab on Grade**
  - Subgrade Preparation and Edge Forms
  - Reinforcing
  - Pouring and Finishing the Concrete
  - Managing Cracking
- **Casting a Concrete Wall**
- **Casting a Concrete Column**
- **One-Way Floor and Roof Framing Systems**
  - One-Way Solid Slab
  - One-Way Concrete Joist (Ribbed Slab)
  - Wide-Module Concrete Joist
  - Designing with One-Way Sitecast Framing Systems
- **Two-Way Floor and Roof Framing Systems**
  - Two-Way Flat Slab and Two-Way Flat Plate
  - Two-Way Waffle Slab
  - Designing with Two-Way Sitecast Framing Systems
- **Sitecast Posttensioned Framing Systems**
- **Other Types of Sitecast Concrete**
  - Tilt-Up Construction
  - Insulating Concrete Forms
  - Shotcrete
  - Architectural Concrete
  - Pavings, Toppings, and Other Uses

Cutting Concrete, Stone, and Masonry

- **Longer Spans in Sitecast Concrete**
- **Designing Economical Sitecast Concrete Buildings**

Preliminary Design of Sitecast Concrete Structures

- **Sitecast Concrete and the Building Codes**
- **Uniqueness of Sitecast Concrete**

Kane Hall, University of Washington, 1969. Architects Walker and McGough made bold use of sitecast concrete construction. *(Photo by Joseph Iano.)*

Concrete that is cast into forms on the building site offers almost unlimited possibilities to the designer. Any shape that can be formed can be cast, with a limitless selection of surface textures, and books on modern architecture are filled with examples of the realization of this extravagant promise. Certain types of concrete elements cannot be precast, but can only be cast on the site: foundation caissons and spread footings, slabs on grade, structural elements too large or too heavy to transport from a precasting plant, elements so irregular or special in form as to rule out precasting, slab toppings over precast floor and roof elements, and many types of structures with two-way slab action or full structural continuity from one member to another. In many cases where sitecast concrete could be replaced with precast, sitecast remains the method of choice simply because of its more massive, monolithic architectural character.

Sitecast concrete structures tend to be heavier than most other types of structures, which can lead to the selection of a precast concrete or structural steel frame instead if foundation loadings are critical. Sitecast buildings are also relatively slow to construct because each level of the building must be formed, reinforced, poured, cured, and stripped of formwork before construction of another level can begin. In effect, each element of a sitecast concrete building is manufactured in place, whereas the majority of the work on steel or precast concrete buildings is done in factories and shops where worker access, tooling, materials-handling equipment, and environmental conditions are generally superior to those on the job site. The technology of sitecasting has evolved, however, in response to its own limitations, with streamlined methods of materials handling, systems of reusable formwork that can be erected or taken down almost instantaneously, extensive prefabrication of reinforcing elements, and mechanization of finishing operations. The rapid pace of this evolution has kept sitecast concrete among the construction techniques most favored by building owners, architects, and engineers.

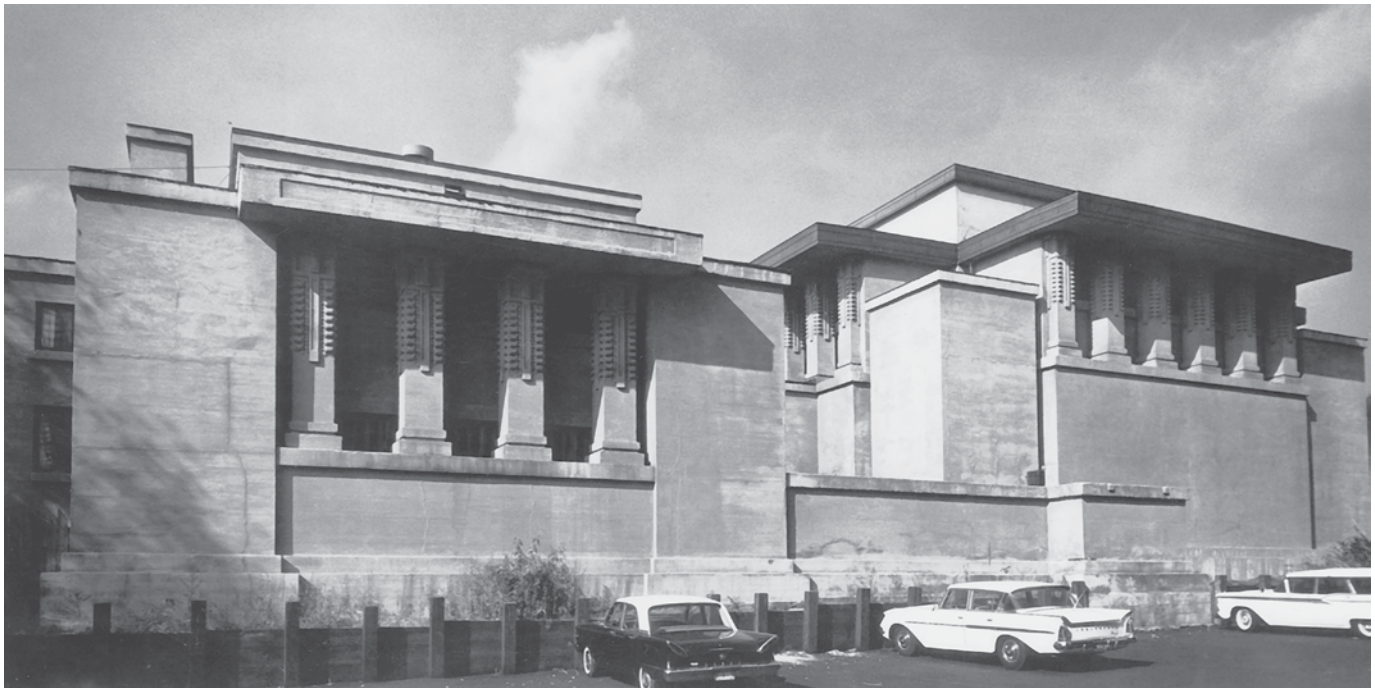


FIGURE 14.1
Unity Temple in Oak Park, Illinois, was constructed by architect Frank Lloyd Wright in 1906. Its structure and exterior surfaces were cast in concrete, making it one of the earliest buildings in the United States to be built primarily of this material. *(Photo by John McCarthy. Courtesy of Chicago Historical Society ICHi-18291.)*

Interactive Exercise

Casting a Concrete Slab on Grade

A concrete *slab on grade* is a level surface of concrete that lies directly on the ground. Slabs on grade are used for roads, sidewalks, patios, airport runways, and basements or ground floors of buildings. A slab-on-grade floor usually experiences little structural stress except a direct transmission of compression between its superimposed loads and the ground beneath, so it furnishes a simple example of the operations involved in the sitecasting of concrete (Figure 14.2).

Subgrade Preparation and Edge Forms

To prepare for the placement of a slab on grade, the unstable topsoil is scraped away to expose the subsoil beneath. If the exposed subsoil is too soft, it is compacted or replaced with more stable material. Next, a layer of 1½-inch-diameter (38-mm) crushed stone at least 4 inches (100 mm) deep, called a *capillary break*, is compacted over the subsoil. This acts as a stable base and drainable layer to keep moisture away from the underside of the slab. Where the slab is not being cast within surrounding walls, a simple edge form—a strip of wood or metal fastened to stakes driven into the ground—is constructed around the perimeter of the area to be poured and is coated with a form release compound to prevent the hardened concrete from sticking (Figure 14.3*a, b*). The top edge of the form is carefully leveled; when the slab is poured, this edge will be used to as a guide to level the slab surface. Where walls surround the slab to be poured, an isolation joint is creating by inserting filler material that allows for future small movements between the finished slab and the surrounding wall (Figure 14.3*c*). The thickness of the slab may range from 3 to 4 inches (75 to 100 mm) for a residential floor, to 6 or 8 inches (150 or 200 mm) for an industrial floor. For interior floor slabs on grade, a *vapor retarder*, usually a heavy plastic sheet, is laid over the crushed stone to further protect the slab from moisture in the ground (Figure 14.3*b*).

Reinforcing

A reinforcing mesh of welded wire reinforcement, cut to a size just a bit smaller than the dimensions of the slab, is laid over the vapor retarder or crushed stone. The reinforcing most commonly used for lightly loaded slabs, such as those in houses, is 6 × 6–W1.4 × W1.4. For slabs in factories,

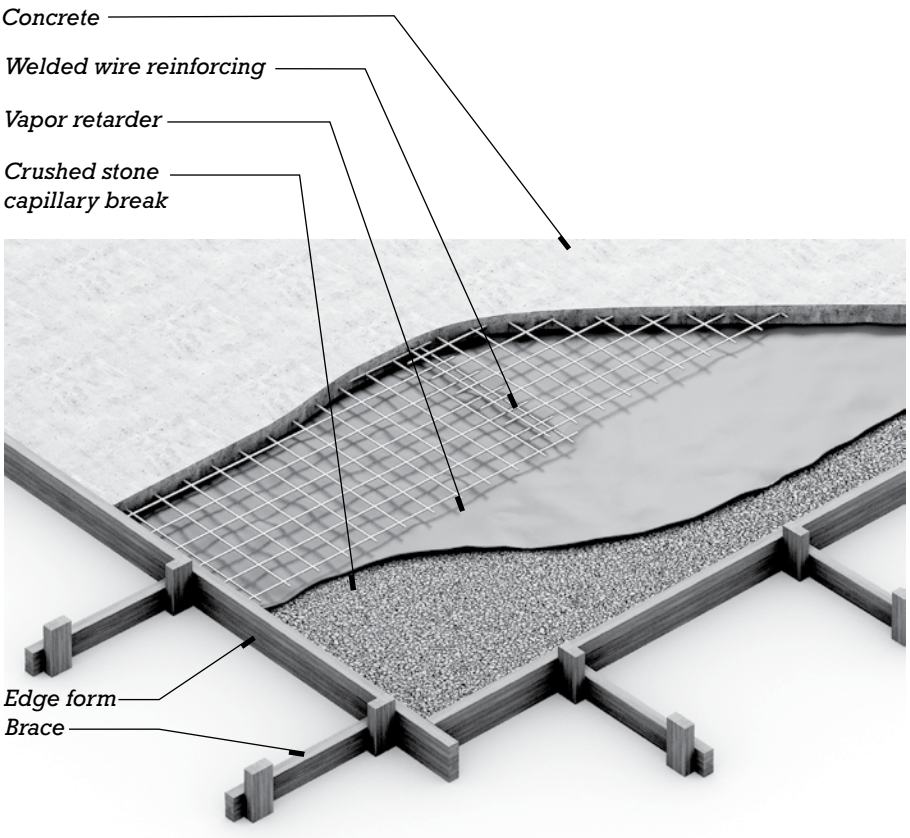
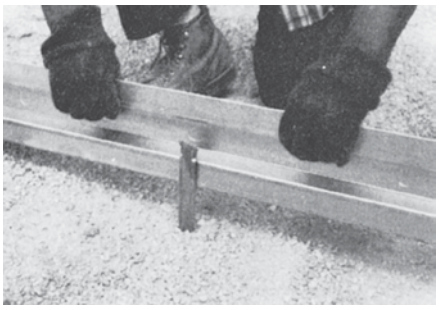


Figure 14.2
The construction of a concrete slab on grade. Notice how the welded wire reinforcement is overlapped where two sheets of fabric meet.

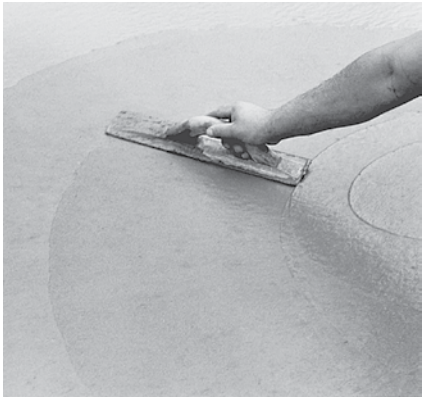

(*a*)

(*b*)

(*c*)

(*d*)

(*e*)


(*f*)

(*g*)

(*h*)

(*i*)

(*j*)

FIGURE 14.3
Constructing and finishing a concrete slab on grade. (*a*) Attaching a slab edge form to a supporting stake. The profile of the edge form causes adjacent pours to interlock. (*b*) To the right, a crushed-stone drainage layer for a slab on grade, and to the left, a slab section ready to pour, with vapor retarder, welded wire reinforcement, and edge forms in place. (*c*) Three-quarter-inch-thick asphalt-impregnated fiberboard is used to form an isolation joint where slab edges abut walls or other vertical surfaces. The plastic cap is removed immediately after slab finishing to leave a clean slot for the later insertion of an elastomeric joint

warehouses, and airports, a fabric made of heavier wires or a grid of reinforcing bars may be used instead. The grid of wires or bars helps protect the slab against cracking caused by concrete shrinkage during curing, temperature stresses, concentrated loads, frost heaving, or settlement of the ground beneath. Fibrous macrofiber reinforcing can also be used in addition to or in place of wire reinforcing for the same purposes.

Pouring and Finishing the Concrete

Casting of the slab on grade commences with the placing of wet concrete in the formwork, using any of the methods described in Chapter 13. The concrete is spread by workers using shovels or rakes until the form is full. Then the same tools, or an immersion vibrator, are used to agitate the concrete slightly, especially around the edges, to eliminate air pockets. Unless the welded wire fabric reinforcing was set on chairs or other supports, the concrete masons reach into the wet concrete with metal hooks and raise this reinforcing to approximately the midheight of the slab. This positions the reinforcing optimally to resist tension caused by forces acting either from above or below the slab.

The first operation in finishing the slab is to *strike off* (or *screed*) the concrete by drawing a stiff plank of wood or metal across the top edges of the formwork to achieve a level concrete surface (Figure 14.3*d*). This is done with an end-to-end sawing motion of the plank that avoids tearing the projecting pieces of coarse aggregate from the surface of the wet concrete. A bulge of concrete is maintained in front of the screed as it progresses across the slab, so that when a low point is encountered, concrete from the bulge will flow in to fill it.

Immediately after striking off the concrete, the slab receives its initial *floating*. This step is usually performed by hand, using flat-surfaced tools, typically 4 to 10 feet (1.2 to 3 m) in length, called *bull floats* or *darbies* (Figure 14.3*e*). These are drawn across the concrete to flatten and consolidate its surface. After this initial floating, the top of the slab is level but still rather rough. If a concrete topping will later be poured over the slab, or if a floor finish of terrazzo, stone, brick, or quarry tile will be applied, the slab may be left to cure without further finishing.

For a smoother surface, additional finishing operations proceed after a period of time during which the concrete begins to stiffen and the watery sheen, called *bleed water*, evaporates from the surface of the slab. First, specially shaped hand tools may be used to form neatly rounded edges around the perimeter of the slab and control joints in the interior. Next, the slab is floated a second time to further consolidate its surface. At this stage, small slabs may be floated by hand (Figure 14.3*f*), but for larger slabs, rotary power floats are used (Figure 14.3*g*). The working surfaces of floats are made of wood or of metal with a slightly rough surface. As the float is drawn across the surface, it gently vibrates the concrete and brings cement paste to the surface, where it is smoothed over the coarse aggregate and into low spots by the float. If too much floating is done, however, an excess of paste and free water rises to the surface and forms puddles, making it almost impossible to get a good finish. Experience on the part of the mason is essential to floating, as it is to all slab finishing operations, to know just when to begin each operation and just when to stop. The floated slab has a lightly textured surface that is appropriate, for example, for outdoor walks and pavings without further finishing.

For a completely smooth, dense surface, the slab is also *troweled*. This is done immediately after the second floating, either by hand, using a smooth, rectangular *steel trowel* (Figure 14.3*h*), or with a *rotary power trowel*. If the concrete mason cannot reach all areas of the slab from around the edges, squares of plywood called *knee boards*, two per mason, are placed on the surface of the concrete. These distribute the mason's weight sufficiently that he or she can kneel on the surface without making indentations. Any marks left by the knee boards are removed by the trowel as the mason works backward across the surface from one edge to the other. If a nonslip surface is required, a stiff-bristled janitor's push broom may be drawn across the surface of the slab after troweling to produce a striated texture called a *broom finish*.

Where a concrete slab must meet narrow floor flatness limits, it may be restraightened after each floating or troweling operation. *Restraightening* is performed with a rectangular flat-bottomed *straightedge*, roughly 10 feet (3 m) in length, which is drawn across the concrete slab surface to remove minor undulations produced during floating or troweling.

sealant. (*d*) Striking off the surface of a concrete slab on grade just after pouring, using a motorized screed. The motor vibrates the screed from end to end to work the wet concrete into a level surface. (*e*) A bull float is used for initial floating, to flatten and consolidate the slab surface immediately after screeding. (*f*) Floating, here performed by hand, brings cement paste to the surface and produces a smoother, denser finish. (*g*) For larger slabs, floating can be done by machine. (*h*) Steel troweling after floating produces a dense, hard, smooth surface. (*i*) Damp curing of the slab, here using a polyethylene plastic sheet cover. (*j*) This slab was cured with a moisture-retaining liquid compound that also provides a protective coating, allowing the next stages of work to proceed sooner on the finished slab. *(Photos a, b, c courtesy of Vulcan Metal; d, e, f, g, h reprinted with permission of the Portland Cement Association, Skokie, IL, from* Design and Control of Concrete Mixtures*, 12th ed.; j by Joseph Iano.)*

Shake-on hardeners are sometimes sprinkled over the surface of a slab between the screeding and floating operations. These dry powders react with the concrete to form a harder, more durable surface for such heavy-wear applications as warehouses and factories.

When the finishing operations have been completed, the slab should be cured under damp conditions for at least a week; otherwise, its surface may crack or become dusty from premature drying. Damp curing may be accomplished by covering the slab with an absorbent material such as sawdust, earth, sand, straw, or burlap and maintaining the material in a damp condition for the required length of time. An impervious sheet of plastic or waterproof paper may be placed over the slab soon after troweling to prevent the escape of moisture from the concrete (Figure 14.3*i*). Or, the concrete surface may be sprayed with one or more applications of a liquid *curing compound*, which forms an almost invisible moisture barrier membrane over the slab surface (Figure 14.3*j*).

No concrete floor is perfectly flat. The normal finishing process produces a surface that undulates between low and high areas that go unnoticed in everyday use. For ordinary concrete slabs, flatness is most commonly specified as the maximum gap size, typically in the range of ⅛ to ⅜ inch (3 to 10 mm), permitted under a 10-foot (3-m) straightedge placed anywhere on the floor. Industrial warehouses that use high-rise forklift trucks, however, require floors whose flatness is controlled to within narrower tolerances. These *superflat floors*, as well as other floors where close control over flatness is desired, are specified according to a more precise system of dimensionless indexes, called *F-numbers*, that correspond to the degrees of flatness (waviness or bumpiness) and levelness (deviation from a horizontal plane or tilt) required, and are produced using special finishing equipment and techniques (Figure 14.4).

Because of their extreme accuracy, laser-guided automatic straightedging machines may be used in the creation of superflat floors. These devices rapidly produce a slab surface that is flat and level to within consistently small tolerances (Figure 14.5).

Floor Use	Flatness F_F	Levelness F_L
Television or movie studio floors	>35	>35
Special-use warehouse, industrial floors, ice skating rinks	30	24
Improved floors, thin-set or resilient flooring	25	17
Commercial building floors, carpeted floors	17	15
Non-critical floors	15	10

FIGURE 14.4
Examples of Minimum Local Values for concrete slab on grade flatness and levelness for various slab uses, measured according to ASTM E1155. Average minimum values for whole floor areas, called Specified Overall Values (not shown here), can also be specified.

Managing Cracking

Because concrete slabs on grade are relatively thin in relation to their horizontal dimensions and normally only lightly reinforced, they are prone to cracking. The stresses that cause cracking may originate from the shrinkage as the concrete cures, thermal expansion and contraction, or differential movement between the slab and abutting building elements. If such cracks are allowed to occur randomly, they can be unsightly and can compromise the functionality of the slab.

The most common method of controlling cracking in concrete slabs on grade is to introduce an organized system of joints into the slab that allow cracking to occur in a neat and visually acceptable pattern. *Contraction joints*, or *control joints*, are intentionally weakened sections created through the concrete slab where the tensile forces caused by concrete drying shrinkage are relieved. They are formed as grooves that extend at least one-quarter of the depth of the slab and are made by either running a special trowel along a straightedge while the concrete is still plastic or sawing partially through the concrete shortly after it begins to harden using a diamond or abrasive saw blade in a power circular saw. To provide a further inducement for cracks to occur at joint locations rather than elsewhere, reinforcing in the slab may be partially discontinued where it crosses these joints. Contraction joint spacing recommendations vary with the thickness of the slab and the shrinkage rate of the concrete. For normal concrete slabs 4 to 8 inches (100 to 200 mm) thick, joint spacings from 11 feet 6 inches to 17 feet 6 inches (3.6 to 5.3 m) are recommended, with thinner slabs requiring closer joint spacing than thicker ones. Control joints should be arranged in perpendicular directions such that they create panels roughly square in proportion.

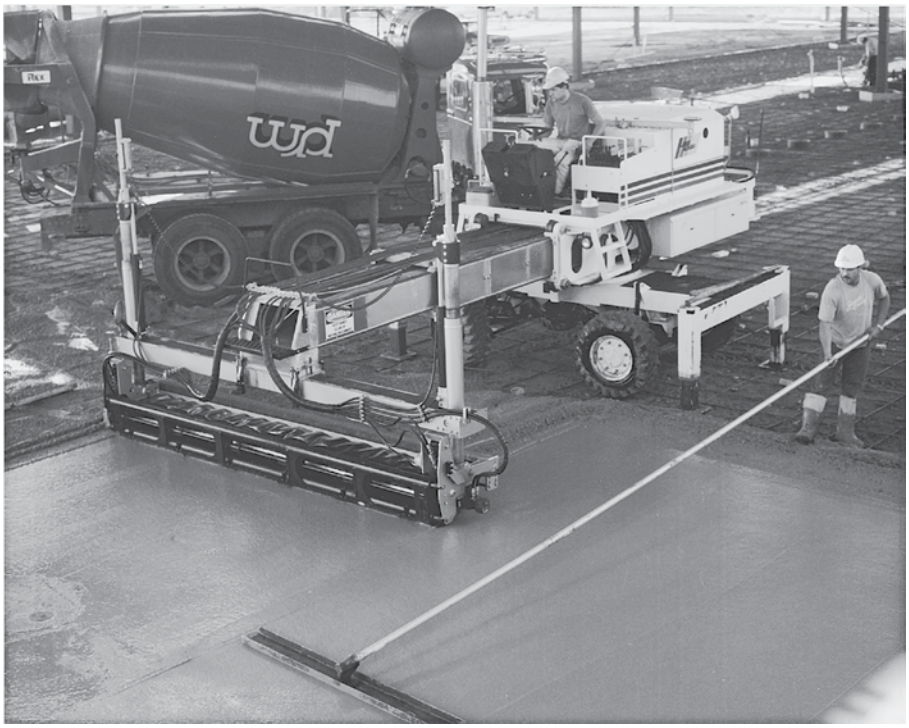


FIGURE 14.5
Guided by a laser beam, the motorized straightedging device on this machine can strike off 240 square feet (22 m²) of slab surface per minute to an extremely exacting standard of flatness. The worker to the right is smoothing the surface with a bull float. *(Photo by Wironen, courtesy of the Laser Screed Co., New Ipswich, NH.)*

Reinforced concrete made "pilotis" possible. The house is in the air, away from the ground; the garden runs under the house, and it is also above the house, on the roof. . . . Reinforced concrete is the means which makes it possible to build all of one material. . . . Reinforced concrete brings the free plan into the house! Floors no longer have to stand simply one on top of the other. They are free. . . . Reinforced concrete revolutionizes the history of the window. Windows can run from one end of the facade to the other. . . .

—Le Corbusier and P. Jeanneret, *Oeuvre Complète* 1910–1929, 1956

Isolation joints, sometimes called *expansion joints*, are formed by casting full-depth preformed joint materials, typically ⅜ to ¾ inch (10 to 20 mm) in width, into the slab (Figure 14.3*c*), completely separating the slab from adjacent elements. Isolation joints allow freedom of movement of the slab with respect to other building parts or other portions of the slab—movements that may occur due to thermal expansion and contraction, structural loading, or differential settlement. Isolation joints are commonly provided where the edge of a concrete slab abuts walls or curbs, as well as around columns or loadbearing walls that pass through the slab within its perimeter. Isolation joints are also used to divide large or irregularly shaped slabs into smaller, more simply shaped areas that are less prone to stress accumulation.

Concrete itself can be manipulated to reduce cracking: Shrinkage-reducing admixtures and some supplementary cementitious materials, such as fly ash, reduce drying shrinkage. Lowering the water–cement ratio of the concrete mix reduces drying shrinkage and results in finished concrete that is stronger and more crack-resistant, though at increased cost. Specially formulated *shrinkage-compensating cements* can counteract drying shrinkage, allowing the casting of large slabs on grade that are free of contraction joints. The amount of reinforcing in the slab can be increased or fibrous reinforcing can be added to the concrete mix to enhance the slab's resistance to tensile forces. Protecting a freshly poured concrete slab from premature drying during the damp curing process reduces cracking while the concrete hardens and ensures that the concrete attains its full design strength.

A slab on grade may also be posttensioned, using level tendons in both directions at the midheight of the slab in place of conventional reinforcing. Posttensioning places the entire slab under sufficient compression to have it remain free from tensile stress under any anticipated condition. Posttensioning eliminates the need for control joints, makes floors more resistant to concentrated

loads, and often permits the use of a thinner slab. It is especially effective for slabs over unstable or inconsistent soils and for superflat floors.

Casting a Concrete Wall

A reinforced concrete wall at ground level usually rests on a poured concrete strip footing (Figures 14.6, 14.7, and 14.8). The footing is formed and poured much like a concrete slab on grade. Its cross-sectional dimensions and its reinforcing, if any, are determined by the structural engineer. A *key*, a groove that will form a mechanical connection to the wall, is sometimes formed in the top of the footing with strips of wood that are temporarily embedded in the wet concrete. In addition, vertical *dowels* consisting of steel reinforcing bars are installed in the footing; these will later be overlapped with the bars in the walls to form a structural

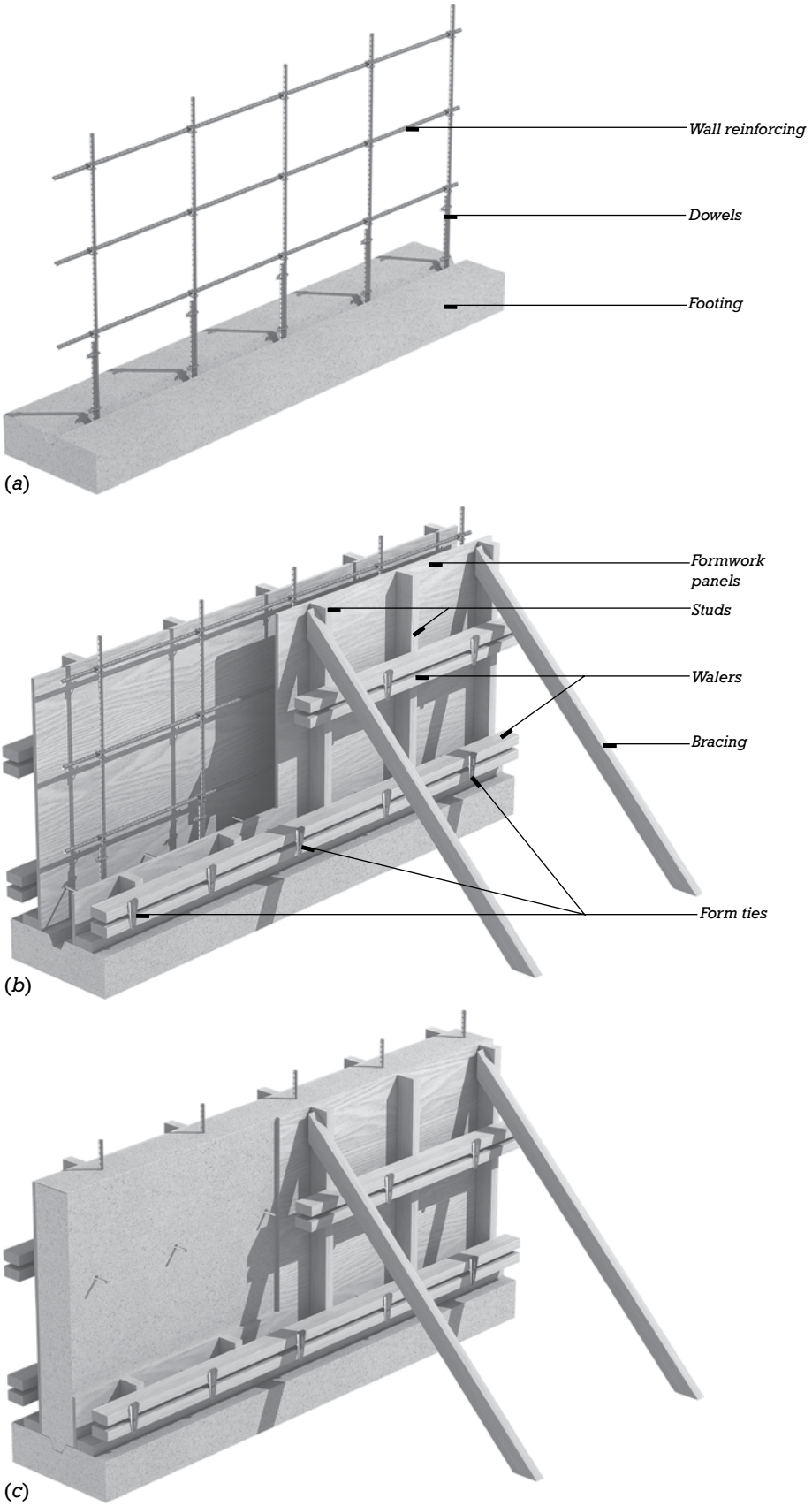


Figure 14.6
Casting a concrete wall. (*a*) Vertical reinforcing bars are wired to the dowels that project from the footing, and horizontal bars are wired to the vertical bars. (*b*) The formwork is erected. Sheets of plywood form the faces of the concrete. They are supported by vertical wood studs. The studs are supported against the pressure of the wet concrete by horizontal walers. The walers are supported by steel rod ties that pass through holes in the plywood to the walers on the other side. The ties also act as spreaders to maintain a spacing between the plywood walls that is equal to the desired thickness of the wall. Diagonal braces keep the whole assembly plumb and straight. (*c*) After the concrete has been poured, consolidated, and cured, the wedges that secure the walers to the form ties are driven out, the formwork is pulled off the concrete, and the projecting ends of the form ties are broken off.

Interactive Exercise

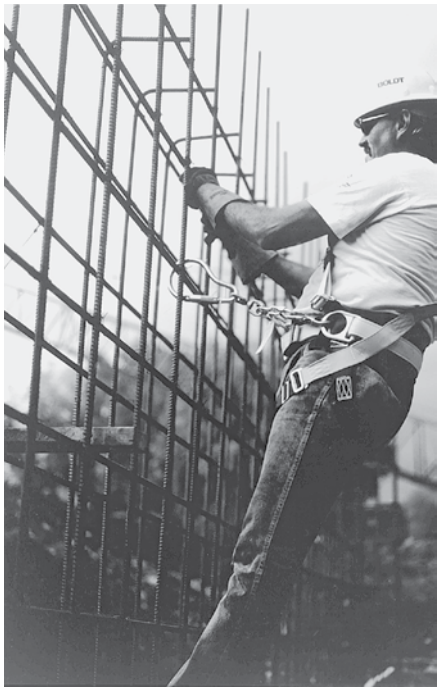


FIGURE 14.7
Protected against falling by a safety harness, a worker stands on the reinforcing bars for a concrete wall to wire another horizontal bar in position. *(Courtesy of DBI-SALA, Red Wing, MN.)*

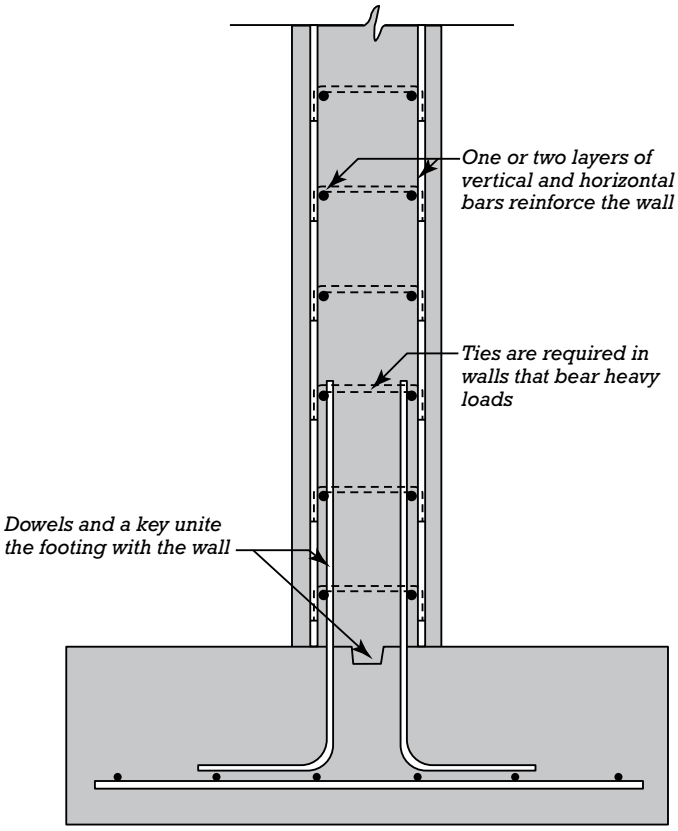


FIGURE 14.8
Section through a reinforced concrete wall, with two layers of horizontal and vertical reinforcing bars for greater strength. The formed key between the wall and footing is more common when only light reinforcing is required. With heavier reinforcing, no key is needed.

connection. After pouring, the top of the footing is screeded; no further finishing operations are required. The footing is left to cure for at least a day before the wall forms are erected.

The wall reinforcing, either in one vertical layer of horizontal and vertical bars at the center of the wall or two layers closer to the faces of the wall, is installed next, with the bars wired to one another at the intersections. The vertical bars are overlapped with the dowels projecting from the footing. L-shaped horizontal bars are installed at wall corners to maintain continuity between the two portions of the wall. If the top of the wall will connect to a concrete floor or another wall above, rods are left projecting from the formwork. These will be embedded in the later pour of concrete.

Wall forms may be custom-built of lumber and plywood for each job, but it is more usual to employ reusable prefabricated panels. The panels for one side of the form are coated with a form release compound, set on the footing, aligned, and braced. The *form ties*, which are small-diameter steel rods specially shaped to hold the formwork together under the pressure of the wet concrete, are inserted through holes provided in the formwork panels and secured to the back of the form by devices supplied with the ties. Both ties and fasteners vary in detail from one manufacturer to another and the type of wall being constructed. An example is shown in Figure 14.9. The ties will pass straight through the concrete wall from one side to the other, with all but the ends remaining embedded permanently in the wall after it is poured.

When the ties are in place and the reinforcing has been inspected, the formwork for the second side of the wall is erected, the *walers* and *braces* are added, and the forms are inspected to be sure that they are straight, plumb, correctly aligned, and adequately tied and braced. A surveyor's transit or laser leveling device is used to establish the exact height to which the concrete will be poured, and this height is marked all around the inside of the forms (Figures 14.10 and 14.11). Pouring may then proceed.

Concrete is brought to the site, test cylinders are made, and a slump test is performed to check for the

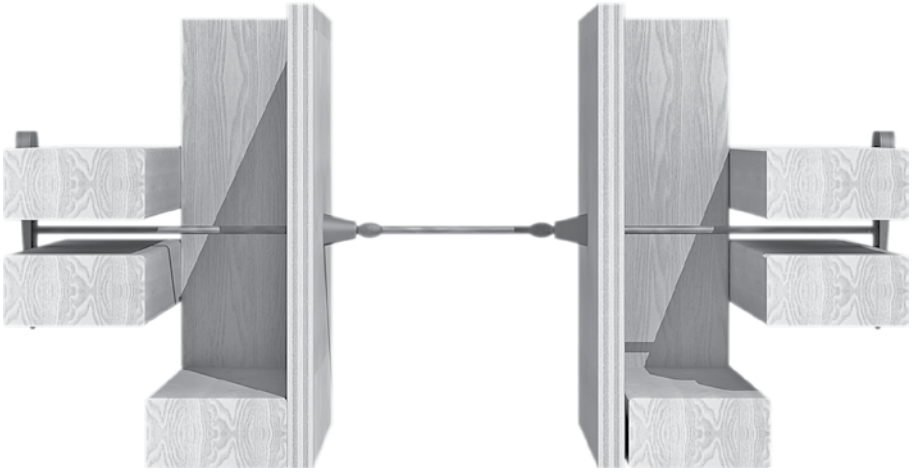


FIGURE 14.9
Detail of a typical form-tie assembly. Plastic cones just inside the faces of the form hold the faces in position. Special hardware at the tie ends clamps against the walers. After the forms have been stripped, the cones will be removed from the concrete and the ties snapped off inside the voids left by the cones. The conical holes may be left open, filled with mortar, or plugged with conical plastic plugs. *(Courtesy of Richmond Screw Anchor Co., 7214 Burns Street, Fort Worth, TX 76118.)*

FIGURE 14.10
Wall formwork, similar to that diagrammed in Figure 14.6, has been erected and bracing is being added. In the background the wall reinforcing is still exposed. Bent reinforcing bars projecting from the top of the formwork will connect to a concrete slab yet to be poured. In the background, bars project vertically, for added wall construction to continue above. *(Photo by Joseph Iano.)*

FIGURE 14.11
Ganged wall forms (described later in this chapter) for a 40-foot (12-m)-plus-tall concrete wall. *(Photo by Joseph Iano.)*

proper pouring consistency. Workers standing on planks at the tops of the forms deposit the concrete into the forms, consolidating it with a vibrator to eliminate air pockets (Figure 14.12). When the form has been filled and consolidated up to the level that was marked inside the formwork, hand floats are used to smooth and level the top of the wall. The top of the form is then covered with a plastic sheet or canvas, and the wall is left to cure.

FIGURE 14.12
Consolidating wet concrete after pouring, using a mechanical vibrator immersed in the concrete. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

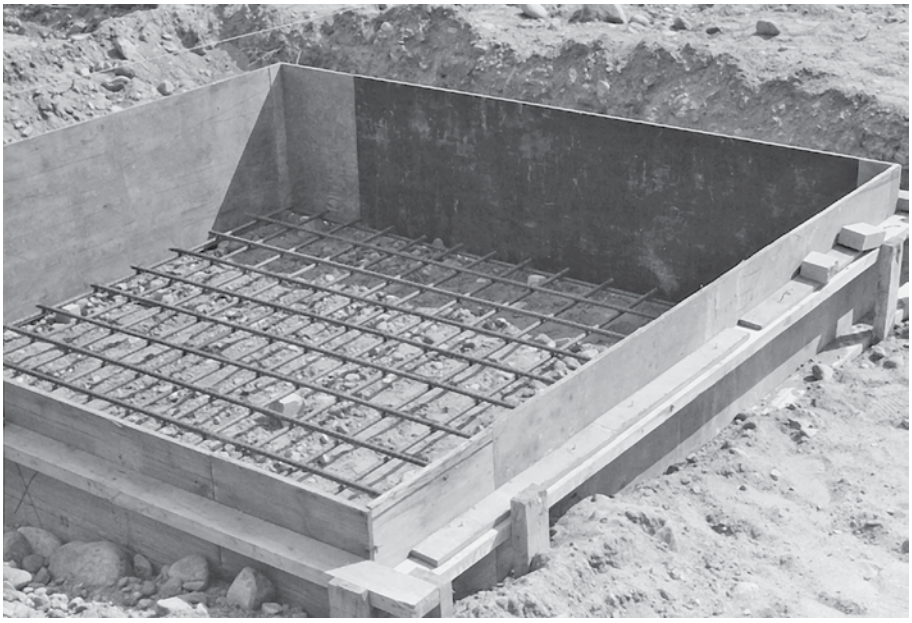
After a few days of curing, the bracing and walers are taken down, the connectors are removed from the ends of the form ties, and the formwork is *stripped* from the wall (Figure 14.13). This leaves the wall bristling with projecting form tie ends. These are twisted off with heavy pliers, and the *form-tie holes* that they leave in the surfaces of the wall are carefully filled with grout. If required, defects in the wall surface, such as those caused by poor consolidation of the concrete, can be repaired at this time. The wall is now complete.

Like concrete slabs on grade, shrinkage cracking in sitecast concrete walls is managed with contraction joints, usually consisting of a pair of grooves on opposite sides of the wall along with partial discontinuity of reinforcing across the joint. Recommended joint spacings range from one times the height of the wall for tall walls to three times the height of the wall for low walls. Contraction joints are also recommended at points of concentrated stress in walls, such as at wall openings or changes in wall height or thickness. Isolation joints are used where cast concrete walls abut other structural elements, and each must remain independent of the other.

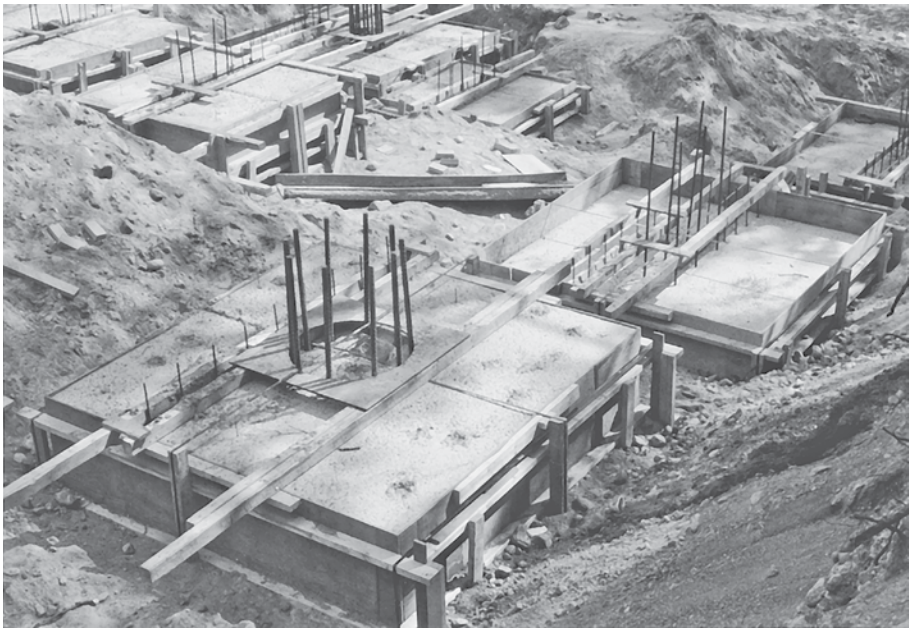
FIGURE 14.13
A concrete wall with formwork stripped. In the foreground and along the bottom of the wall, the form tie ends have been snapped off. Elsewhere, they still protrude from the wall. *(Photo by Joseph Iano.)*

Casting a Concrete Column

A column is formed and cast much like a wall, with a few important differences. The footing is usually an isolated column footing, a pile cap, or a caisson rather than a strip footing (Figure 14.14). The dowels are sized and spaced in the footing to match the vertical bars in the column. The cage of column reinforcing is assembled with wire ties and hoisted into place over the dowels. If space is too tight in the region where the vertical bars and dowels overlap, the bars may be spliced end-to-end with welds or mechanical connectors instead (Figure 13.25). The column form may be a rectangular box of plywood or composite panels, a cylindrical steel or plastic tube bolted together in halves so that it can later be removed, or a waxed cardboard tube that is stripped after curing by unwinding the layers of paper that make up the tube (Figures 14.15 and 14.16). Unless a rectangular column is very broad and wall-like, form ties through the concrete are not required. The vertical bars project from the top of the column to overlap or splice to



(*a*)



(*b*)

Figure 14.14
(*a*) A column footing almost ready for pouring but lacking dowels. The reinforcing bars are supported on pieces of concrete brick. (*b*) Column footings poured with projecting dowels to connect to both round and rectangular columns. *(Photos by Edward Allen.)*

Figure 14.15
In the foreground, a square column form is tied with pairs of L-shaped steel brackets. In the background, a worker braces a round column form made of sheet steel. *(Courtesy of the Ceco Corporation, Oakbrook Terrace, IL.)*

Interactive Exercise

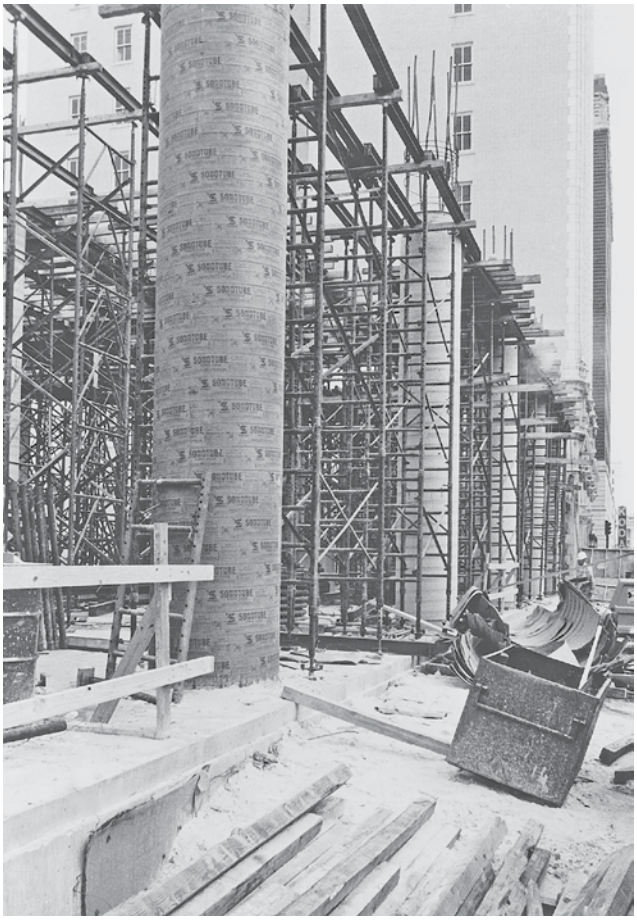


Figure 14.16
Round columns may also be formed with single-use heavy cardboard tubes. Notice the density of the steel shoring structure that is being erected to support the slab form, which will carry a very heavy load of wet concrete. *(Courtesy of Sonoco Products Company.)*

the bars in the column for the story above, or they are bent over at right angles to splice into the floor or roof structure above. Where vertical bars overlap, the tops of the bars from the column below are offset (bent inward) by one bar diameter to avoid interference.

One-Way Floor and Roof Framing Systems

One-Way Solid Slab

A *one-way solid slab* (Figures 14.17, 14.18, and 14.19) spans across parallel lines of support furnished by walls or columns and beams. The walls and columns are poured before the formwork for the slab is erected, but the forms for girders and beams are nearly always built continuously with those for the slab, and girders, beams, and slab are poured simultaneously as a single piece.

The girder and beam forms are erected first, then the slab forms. The formwork is supported on metal or wood framing that is, in turn, supported on temporary, adjustable-length columns called *shores*. The weight of uncured concrete that must be supported is enormous, and the temporary framing and shoring must be both strong and closely spaced. Formwork is, in fact, designed by a contractor's structural engineers as carefully as it would be if it were a permanent building, because a structural failure in formwork is an intolerable risk to workers and property.

Edges of concrete structural elements may be beveled or rounded by inserting shaped strips of wood or plastic into the corners of the formwork to produce the desired profile. This is done because sharp edges of concrete can break off during form stripping to leave a ragged edge that is almost impossible to patch. In service, sharp edges can also be easily damaged by, and are potentially damaging to, people and furniture.

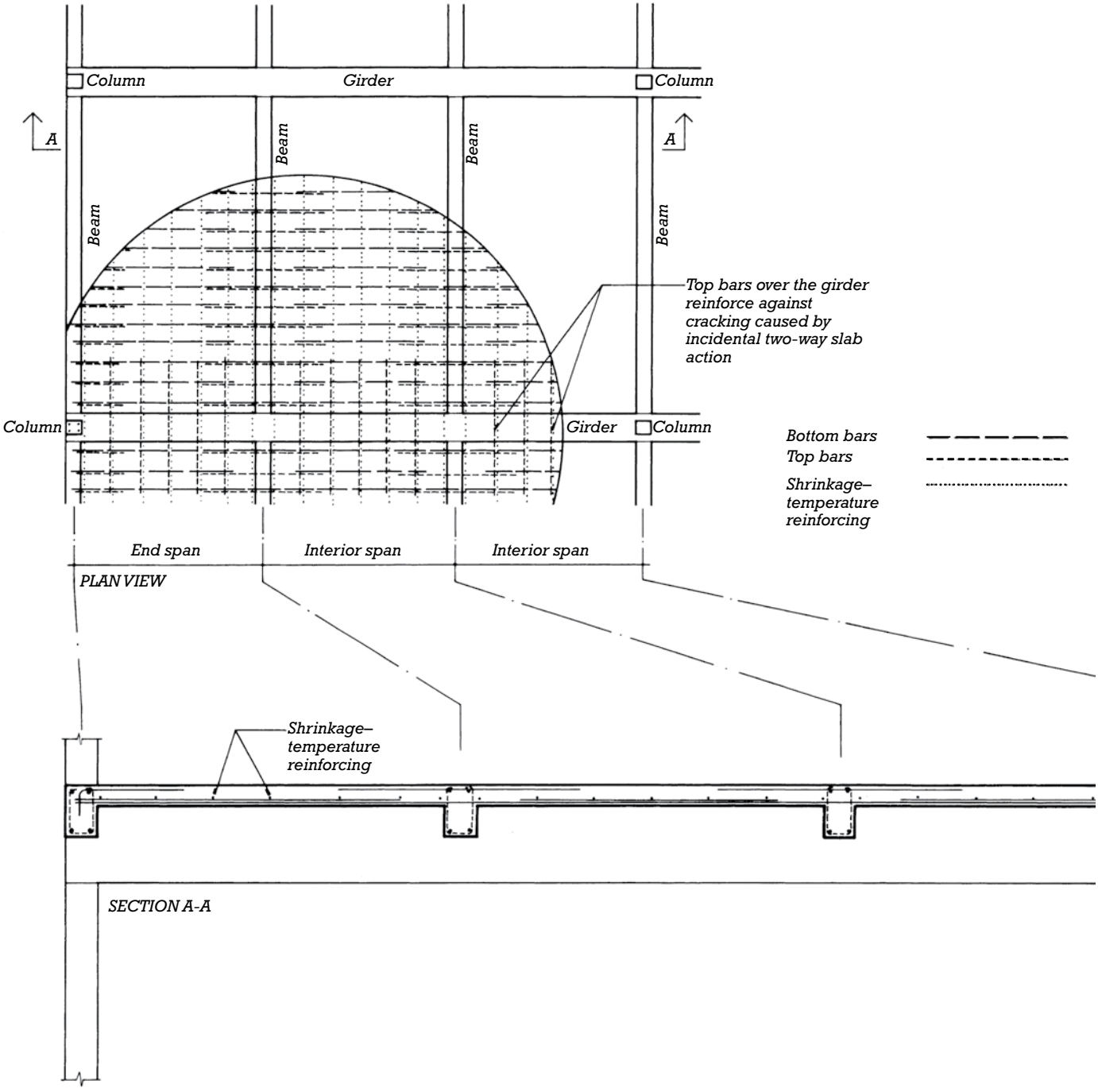


FIGURE 14.17

Plan and larger-scale section of a typical one-way solid slab system. For the sake of clarity, the girder and beam reinforcing are not shown in the plan, and the girder and column reinforcing are left out of the section. The slabs span between the beams, the beams are supported by the girders, and the girders rest on the columns.

A form release compound is applied to formwork surfaces that will be in contact with concrete. Then, in accordance with reinforcing diagrams and schedules prepared by the structural engineer, the girder and beam reinforcing—bottom bars, top bars, and stirrups—is installed in the forms, supported on chairs and bolsters to maintain the required cover of concrete. Next, the slab reinforcing—bottom bars, top bars, and shrinkage–temperature bars—is placed on bolsters. After the reinforcing and formwork have been inspected, the

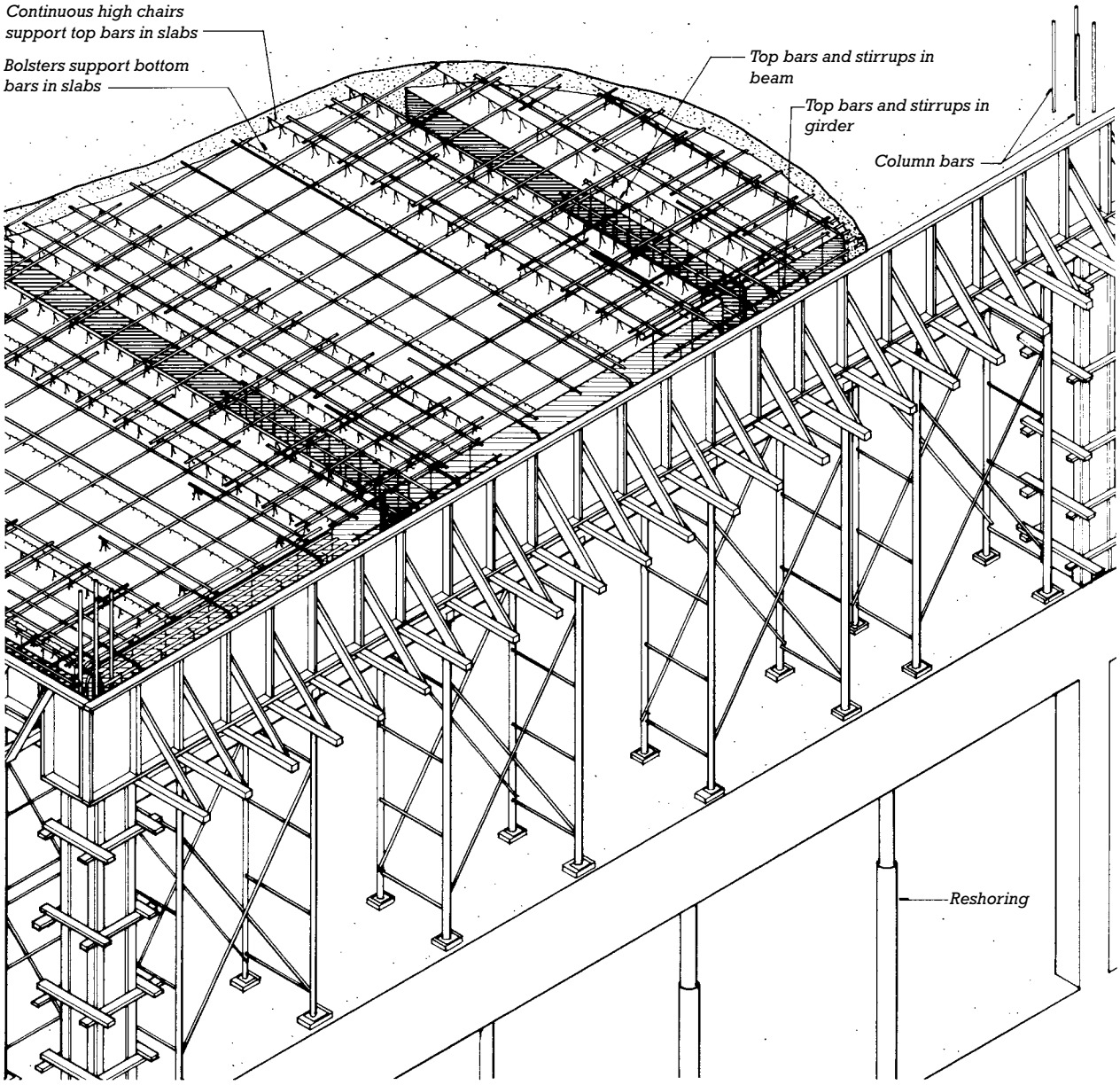


FIGURE 14.18
Isometric view of a one-way solid slab system under construction. The slab, beams, and girders are created in a single pour.

girders, beams, and slab are poured in a single operation, with sample cylinders being made for later testing to be sure that the concrete meets its specified strength. One-way slab depths are typically 4 to 10 inches (100 to 250 mm), depending on the span and loading intensity. The top of the slab is finished in the same manner as a slab on grade, usually to a steel trowel finish, and the slab is sealed or covered for damp curing.

The only components left projecting above the slab surface at this stage are the offset column bars, which are now ready to overlap with, or splice to, the column bars for the floor above.

When the slab and beams have attained enough strength to support themselves safely, the formwork is stripped and the slabs and beams are *reshored* with vertical props to temporarily relieve them of loads until they have reached greater strength. Meanwhile, the formwork is cleaned and moved up a level above the slab just poured, where the cycle of forming, reinforcing, and pouring is repeated (Figure 14.20). By stripping the formwork as soon as possible, formwork can more sooner be made available for the next-level pour, and the underside of the slab just cast becomes exposed, allowing the start of other trade work, such as plumbing or sprinklers.

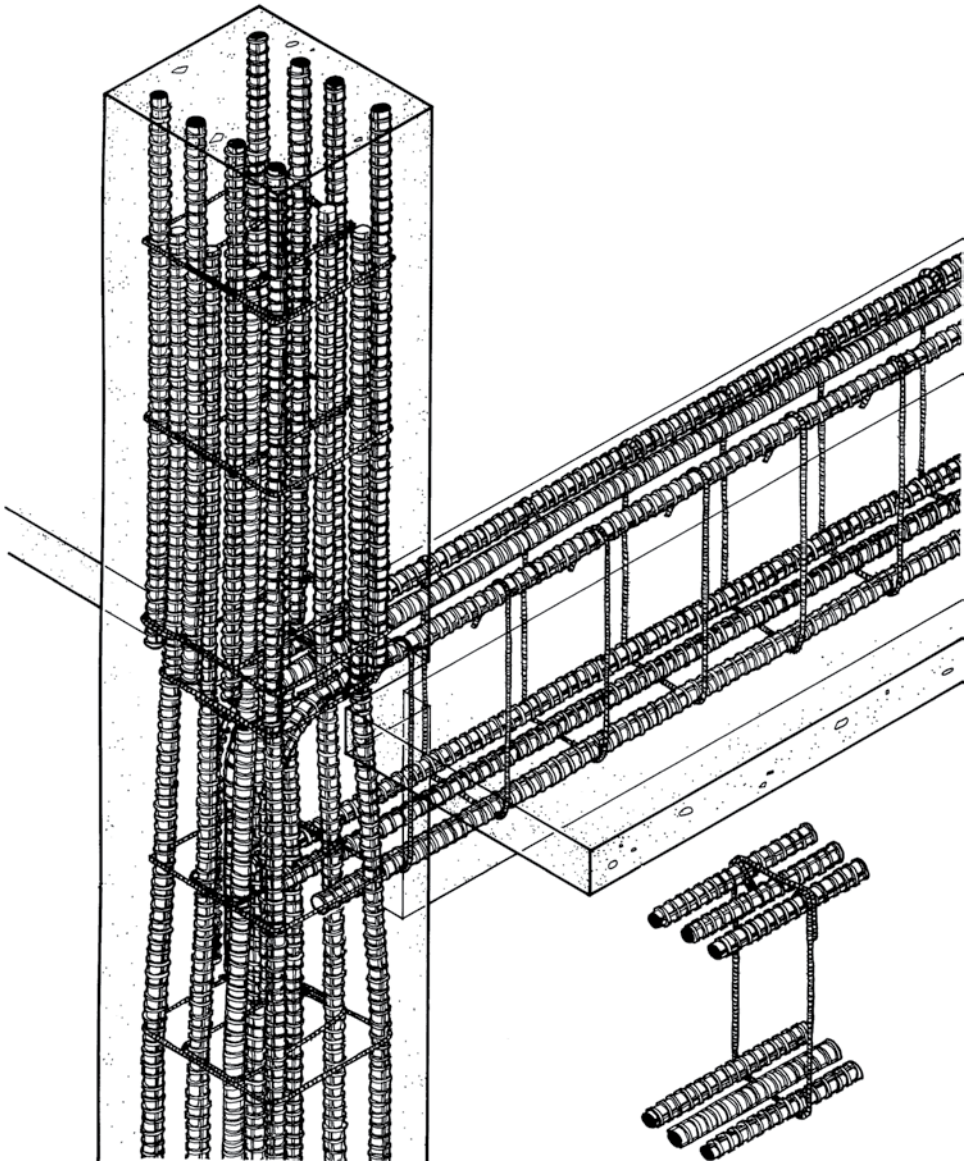


FIGURE 14.19
An example of a beam–column connection in a one-way solid slab structure, with the slab reinforcing omitted for clarity. Notice how the column bars are spliced by overlapping them just above floor level. The bars from the column below are offset at the top so that they lie just inside the bars of the column above at the splice. Structural continuity between the beam and column is established by running the top bars from the beam into the column. U-stirrups are shown in the beam; closed stirrup ties, shown in the inset detail, are often used instead.

Ordinarily, the most efficient and economical concrete beam is one whose depth is two to three times its breadth. One-way solid slabs are often supported, however, by beams that are several times as broad as they are deep, called *slab bands* (Figure 14.21). Banded slab construction offers two kinds of economy: The width of the slab band reduces the span between the bands, which can result in a reduced thickness for the slab and consequent savings of concrete and reinforcing steel. Also, the reduced depth of the slab band compared to a more conventionally proportioned beam allows reduction of the story height of the building, with attendant economies in columns, cladding, partitions, and vertical runs of piping and ductwork.

One-Way Concrete Joist (Ribbed Slab)

As one-way solid slab spans increase, a progressively thicker slab is required. Beyond a certain span, the slab becomes so thick that its own weight becomes an excessive burden, unless a substantial portion of the nonworking concrete in the lower part of the slab can be eliminated to lighten the load. This is the rationale for the *one-way concrete joist system* (Figures 14.23 through 14.26), also called a *ribbed slab.* The bottom steel is concentrated in spaced ribs (joists). The thin slab that spans across the top of the joists is reinforced only by shrinkage–temperature bars. There is

Figure 14.20
Reshoring supports the first slab above grade. Above that, formwork for the next-level concrete slab has been assembled. The columnar supports for reshoring and formwork look similar. But reshoring is installed after the formwork has been removed and each column makes direct contact with the underside of the slab above. The supports for formwork make contact with the underside of the formwork. *(Photo by Joseph Iano.)*

Figure 14.21
Banded slab construction. Note also the grouted slab band posttensioning cable ends and reshoring of the upper slabs. *(Photo by Joseph Iano.)*

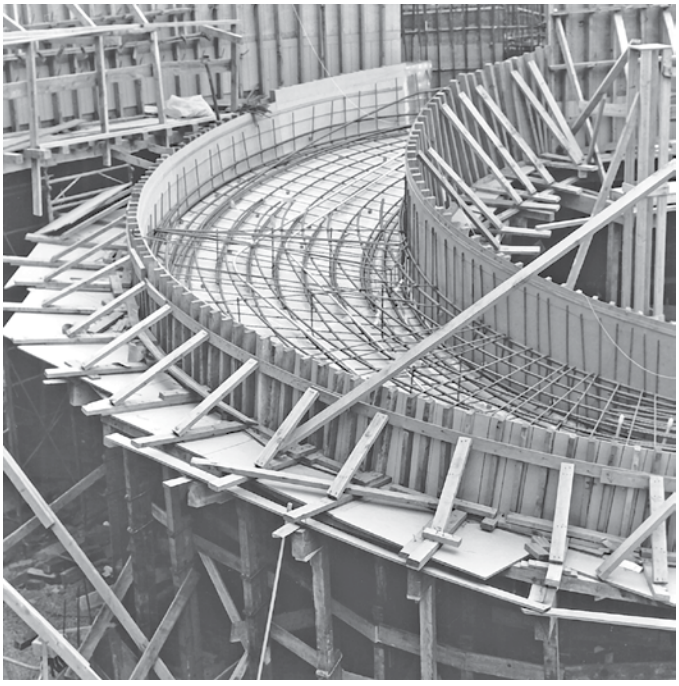


Figure 14.22
This helical ramp is a special application of one-way solid slab construction. *(Courtesy American Plywood Association.)*

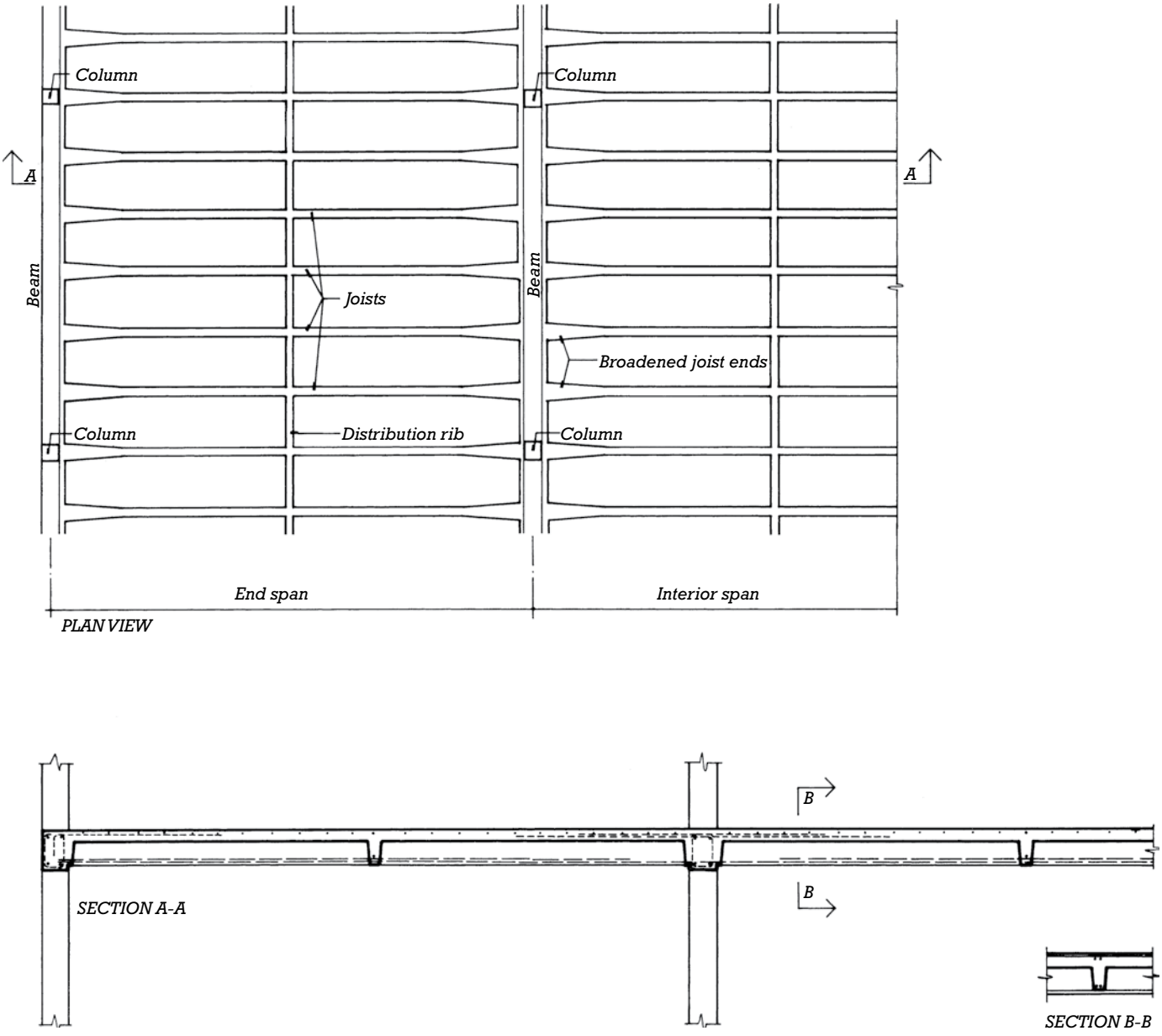


FIGURE 14.23

Plan and larger-scale section of a typical one-way concrete joist system. For the sake of clarity, no reinforcing is shown in the plan, and the column reinforcing is not shown on the section. All bottom and top reinforcing occurs in the ribs, and all shrinkage–temperature bars are placed in the slab.

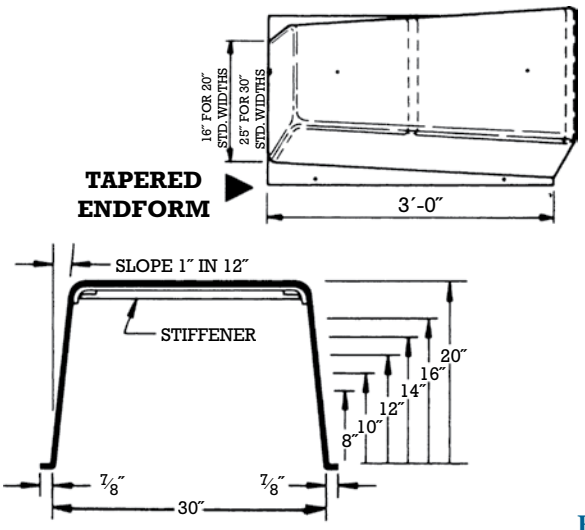


FIGURE 14.24
Standard steel form dimensions for one-way concrete joist construction. (One inch equals 25.4 mm.) *(Courtesy of the Ceco Corporation, Oakbrook Terrace, IL.)*

FIGURE 14.25
Reinforcing being placed for a one-way concrete joist floor. Electrical conduits and boxes have been put in place, and welded wire fabric is being installed as shrinkage–temperature reinforcing. Both the tapered end pans and the square endcaps for the midspan distribution rib are clearly visible. *(Courtesy of the Ceco Corporation, Oakbrook Terrace, IL.)*

FIGURE 14.26
A one-way concrete joist system after stripping of the formwork, showing broadened joist ends at the lower edge of the photograph and a distribution rib in the foreground. The dangling wires are hangers for a suspended finish ceiling. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

little concrete in this system that is not working, with the result that a one-way concrete joist system can efficiently and economically span considerably longer distances than a one-way solid slab. Each joist is reinforced as a small beam, except that stirrups are not usually used, because of the restricted space in the narrow joist. Instead, the ends of the joists are broadened sufficiently that the concrete itself can resist the diagonal tension (shear) forces.

The joists are formed with metal or plastic *pans* supported on a temporary plywood deck. Pans are available in two standard widths, 20 inches (508 mm) and 30 inches (762 mm), and in depths ranging up to 20 inches (508 mm), as shown in Figure 14.24. The sides of the pans taper from bottom to top, to allow them to drop easily from the hardened concrete. The joist width can be varied by placing the rows of pans closer together or farther apart. The bottom of each joist is formed by the wood deck on which the pans are placed. The joist ends are broadened with standard end pans whose width tapers. A *distribution rib* is sometimes formed across the joists at midspan to distribute concentrated loads to more than one joist. After application of a form release compound, the beam and joist reinforcing are placed, the shrinkage–temperature bars are laid crosswise on bolsters over the pans, and the entire system is poured and finished.

One-way concrete joists are usually supported on *joist bands*, which are broad beams that are only as deep as the joists. Although a deeper beam would be more efficient structurally, a joist band is formed by the same plywood deck that supports the pans, which eliminates expensive beam formwork entirely and produces a simpler underside of slab profile with a uniform floor-to-ceiling height throughout.

Wide-Module Concrete Joist

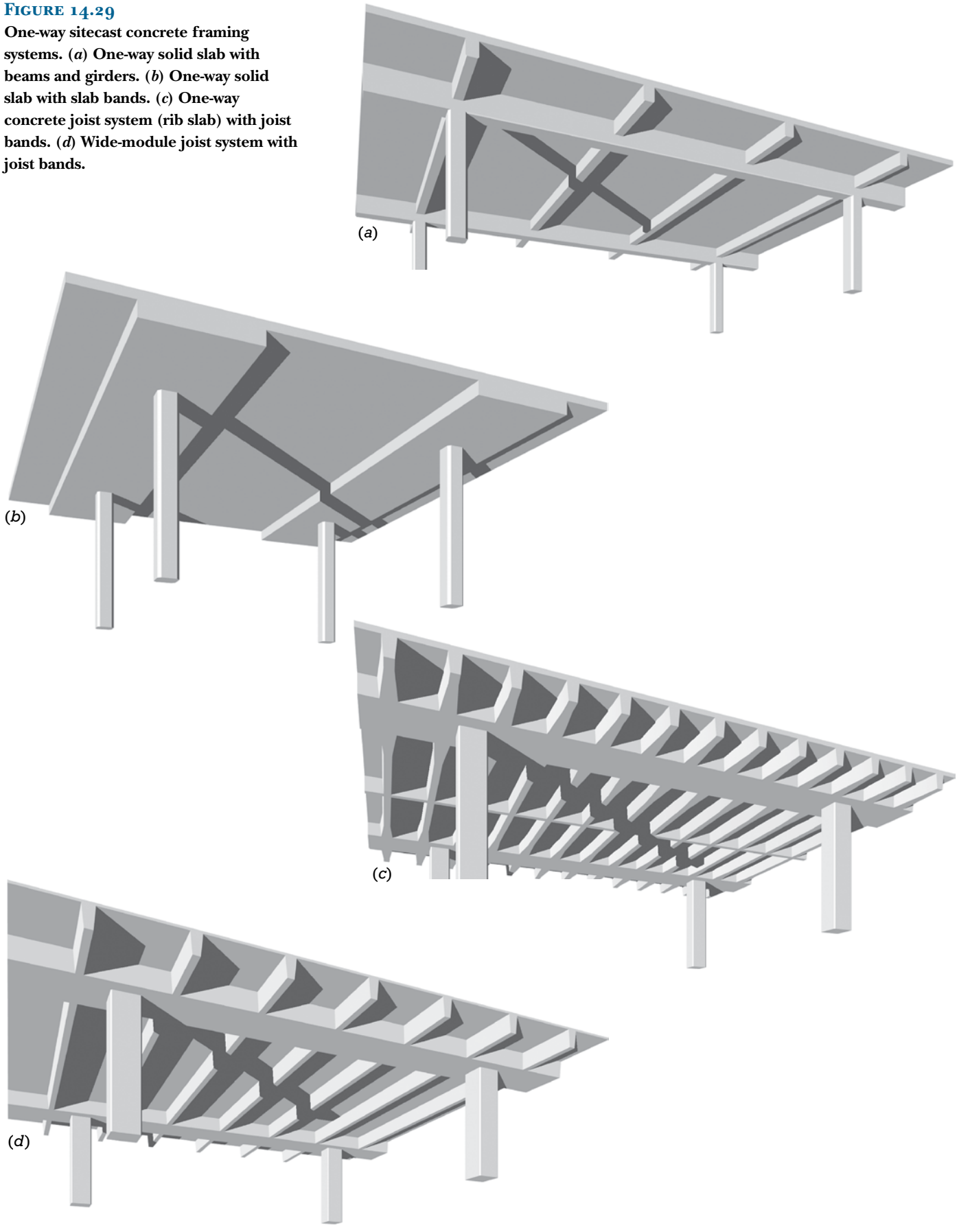
When fire resistance requirements of the building code dictate a slab thickness of 4½ inches (115 mm) or more, the slab is capable of spanning a much greater distance than the normal space between joists in a one-way concrete joist system. In this circumstance, the *wide-module concrete joist system*, also called the *skip-joist system*, may be used, in which the joists are placed 4 to 6 feet (1220 to 1830 mm) apart. The name "skip-joist" arose from the original practice of achieving this wider spacing by laying strips of wood over alternate joist cavities in conventional joist pan formwork to block out the concrete. Pans are now specially produced for wide-module construction (Figures 14.27 and 14.28).

Because wide-module joists must each carry about double the weight carried by conventionally spaced joists, stirrups are required near the

FIGURE 14.27
Formwork for a wide-module concrete joist system. These pans have been placed over a flat plywood deck, which will also serve to form the bottoms of the joist band beams. *(Courtesy of the Ceco Corporation, Oakbrook Terrace, IL.)*

FIGURE 14.28
The underside of the finished wide-module joists, joist bands, and slab. *(Courtesy of the Ceco Corporation, Oakbrook Terrace, IL.)*

FIGURE 14.29
One-way sitecast concrete framing systems. (*a*) One-way solid slab with beams and girders. (*b*) One-way solid slab with slab bands. (*c*) One-way concrete joist system (rib slab) with joist bands. (*d*) Wide-module joist system with joist bands.



ends of each joist. If conventional U-stirrups are used, they must be installed on a diagonal as seen from above, in order to fit into the narrow joist, or single-leg stirrups may be used instead.

Designing with One-Way Sitecast Framing Systems

One-way framing systems (Figure 14.29) are best suited to floor plans with rectangular framing bays, since where bays are closer to square in proportion, more structurally efficient two-way systems may be used. Where spans do not exceed approximately 20 feet (6 m), one-way solid slab construction is an economical choice. Or, for longer spans, one-way solid slab with slab bands or one-way joist systems may be used. One-way slab and beam systems are a good choice where floor loads are very high. Any system with a deep connection where the columns meet the slab, for example slab and beam and one-way joist, are good choices where the system must act as a moment frame to resist lateral wind and earthquake forces. (A deeper column-to-slab connection provides more capacity to develop resistance to rotational forces in the connection.)

Two-Way Floor and Roof Framing Systems

Two-Way Flat Slab and Two-Way Flat Plate

Where columns supporting a slab can be arranged in bays that are square or nearly square in proportion, two-way concrete framing systems that are more economical than one-way systems can be used. A *two-way solid slab* system is rarely seen, though it is occasionally used for very heavily loaded industrial floors; in such a system, the slab is supported by a grid of beams running in both directions over the columns. Most two-way floor and roof framing systems, however, even for heavy loadings, are made without beams. The slab is reinforced in such a way that the varying stresses in the different zones of the slab are accommodated within a uniform thickness of concrete. This simplifies formwork construction and reinforcing bar patterns considerably.

The *two-way flat slab* (Figure 14.30), a system suited to heavily loaded buildings such as storage and industrial buildings, illustrates this concept. The formwork is completely flat except for a thickening of the concrete to resist the high shear forces around the top of each column. Traditionally, this thickening was accomplished with both a funnel-shaped *mushroom capital* and a square *drop panel*, but today the capital is eliminated to reduce the formwork cost, leaving a drop panel to do the work alone (Figure 14.31). Typical depths for the slab itself range from 6 to 12 inches (150 to 300 mm).

Reinforcing for a two-way slab is laid in both directions in half-bay-wide strips of two fundamental types: *Column strips* are designed to carry the higher bending forces encountered in the zones of the slab that cross the columns. *Middle strips* have a lighter reinforcing pattern. Shrinkage–temperature steel is not needed in two-way systems because the concrete is already reinforced in both directions to resist bending. The drop panel and capital (if any) have no additional reinforcing beyond that provided by the column strip; the greater thickness of concrete furnishes the required shear resistance.

In more lightly loaded buildings, such as hotels, hospitals, dormitories, and apartment buildings, the slab need not be thickened at all over the columns. This makes the formwork extremely simple and even allows some columns to be moved off the grid somewhat if it will improve the arrangement of the floor plan. The completely flat ceilings of this system allow room partitions to be placed anywhere with equal ease. Because there are no beams or girders, only a thin slab, the story heights of the building may be kept to an absolute minimum, which reduces the costs of exterior cladding and other systems. Typical slab depths for such a *two-way flat plate* system range from 5 to 12 inches (125 to 305 mm) (Figure 14.32).

The zones along the exterior edges of both the two-way flat slab system and the two-way flat plate system require special attention. To take full advantage of structural continuity, the slabs should be cantilevered beyond the last row of columns a distance equal to about 30 percent of the interior span. If such a cantilever is impossible, additional reinforcing must be added to the slab edges to carry the higher stresses that will result.

Because a two-way flat plate has no drop panel, it requires additional reinforcing in the slab at the top of each column to resist the high shear stresses that occur in this region. This can be accomplished with added steel reinforcing bars or other specially designed reinforcing, such as the one shown in Figure 14.33.

Two-Way Waffle Slab

The *waffle slab*, or *two-way concrete joist system* (Figure 14.34), is the two-way equivalent of the one-way concrete

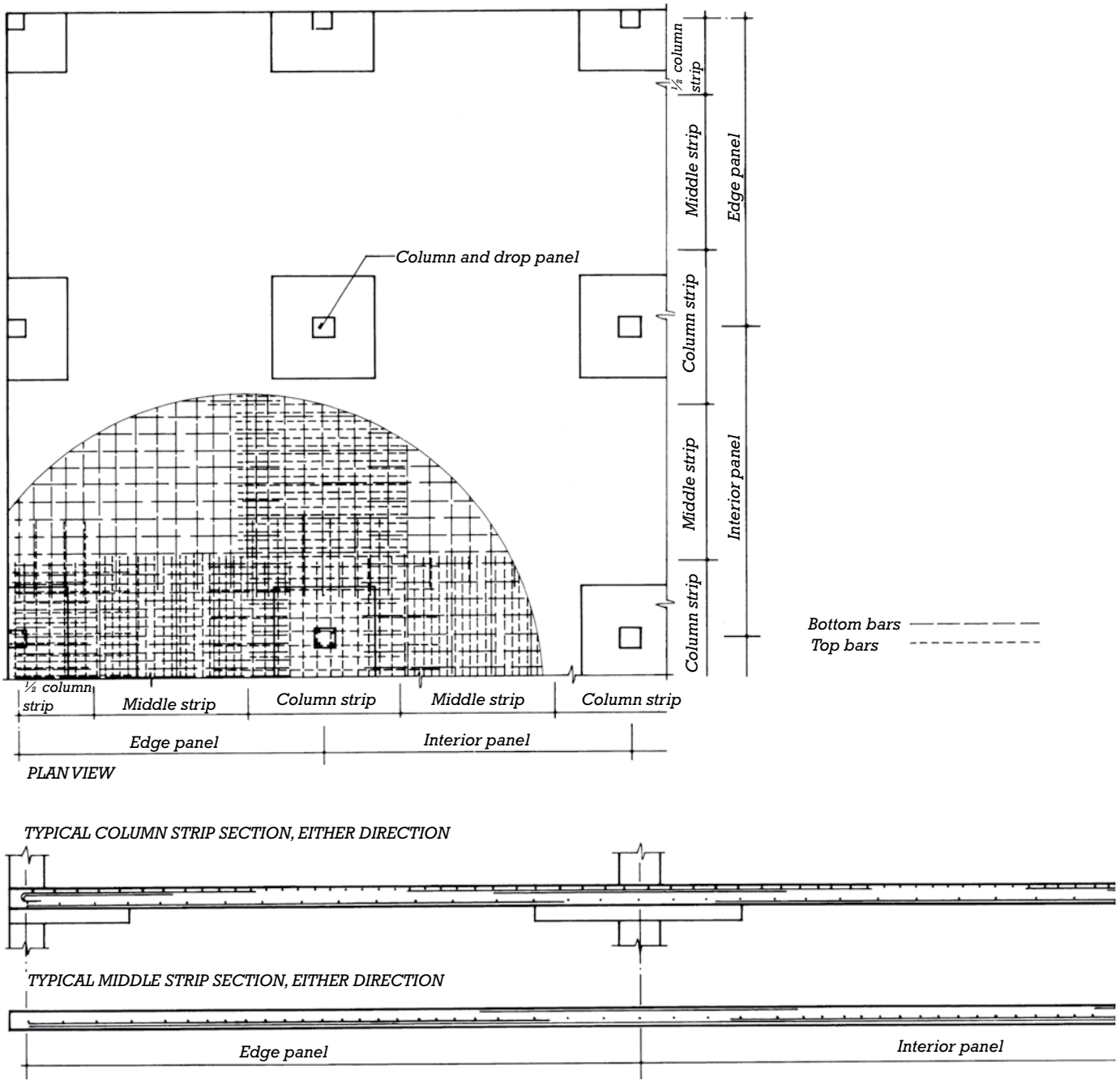


Figure 14.30

Plan and larger-scale section of a typical two-way flat slab system. The reinforcing pattern consists of column strips and middle strips, with each strip changing pattern slightly around the perimeter of the building to accommodate the different bending forces that occur in the edge panels. The system shown uses only drop panels without mushroom capitals. The reinforcing in a two-way flat plate system is essentially identical to this example; the only difference is that the flat plate has no drop panels.

FIGURE 14.31
Top of column conditions for two-way concrete slab systems. *Top*: Flat plate construction omits any thickening of the slab near the column. Shear stresses at the column–slab connection are resisted with steel reinforcing within the slab (not shown in this diagram). *Middle and bottom*: Flat slab construction adds concrete drop panels, and sometimes, mushroom capitals as well, where columns meet slabs.

FIGURE 14.32
Flat plate construction for a high-rise apartment building. Columns located off of a regular grid are readily accommodated by this system. Note the cantilevered slab edges, very thin floor slabs, and minimal floor-to-floor heights. Reshoring is in place on two of the upper floors. A climbing system of formwork and protection from the weather tops out the structure in progress. *(Photo by Joseph Iano.)*

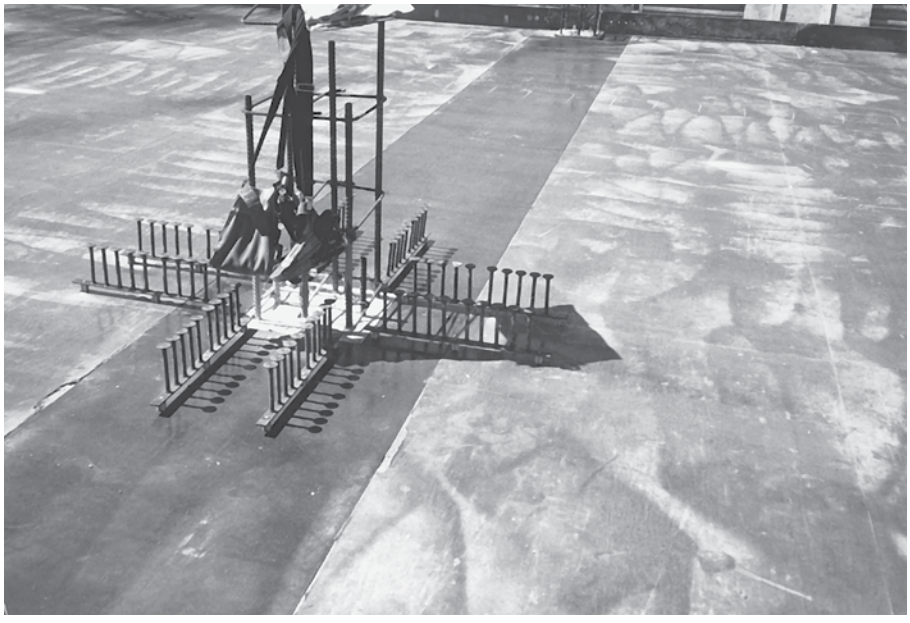


FIGURE 14.33
The high shear forces around the top of the column require either added conventional reinforcing or a system such as the Studrails system shown here. The remainder of the slab reinforcing has not yet been installed. *(U.S. and Canada patents Nos. 4406103 and 1085642, respectively. Licensee: DEHA, represented by DECON, 105C Atsion Rd., P.O. Box 1575, Medford, NJ 08055-6675 and 35 Devon Road, Bramton, Ontario L6T 5B6. U.S.: 1-800-527-7245.)*

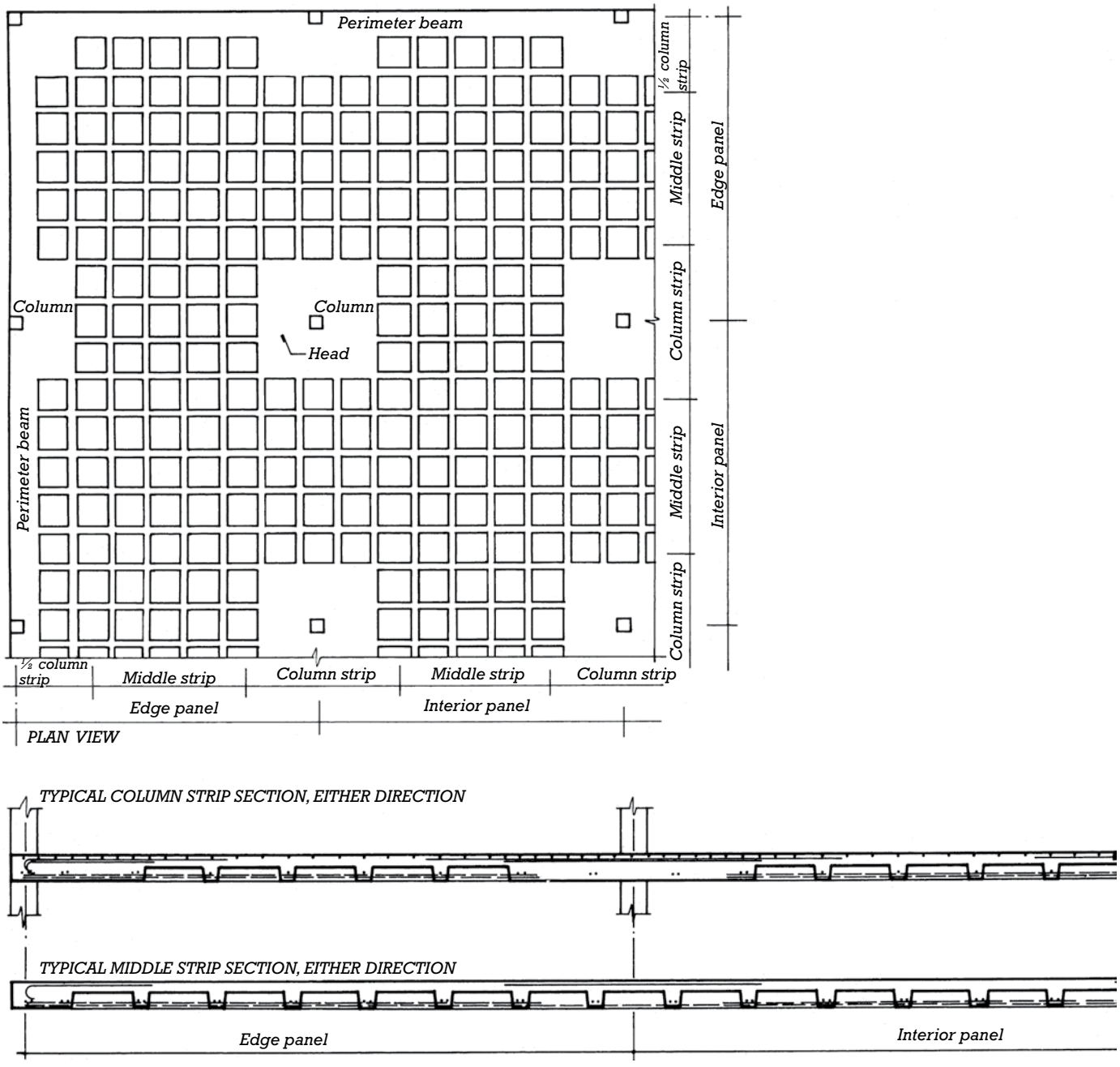


FIGURE 14.34
Plan and larger-scale section of a typical two-way concrete joist system, also known as a waffle slab. For the sake of clarity, no reinforcing is shown on the plan drawing, and the section does not show the welded wire fabric that is spread over the entire form before pouring.

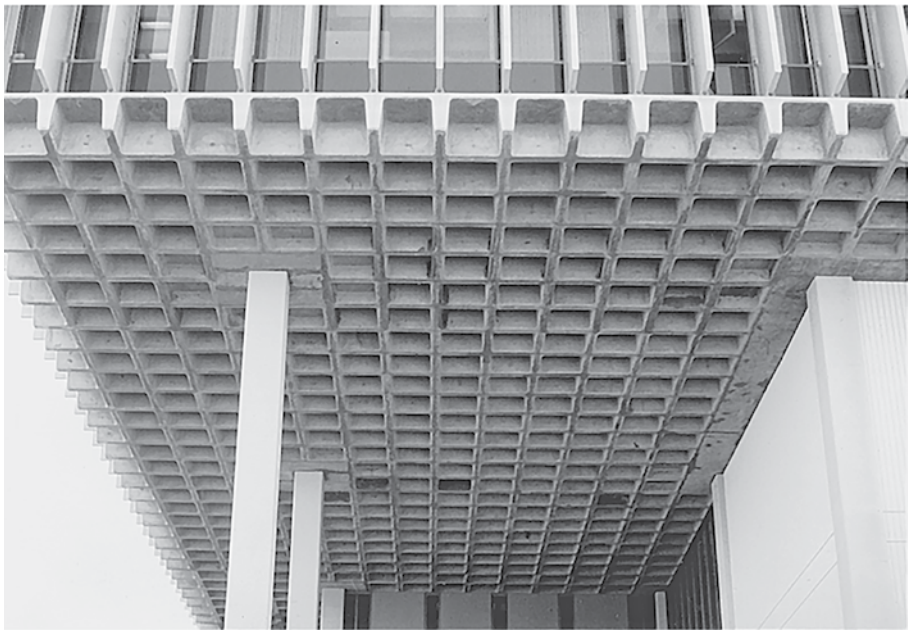


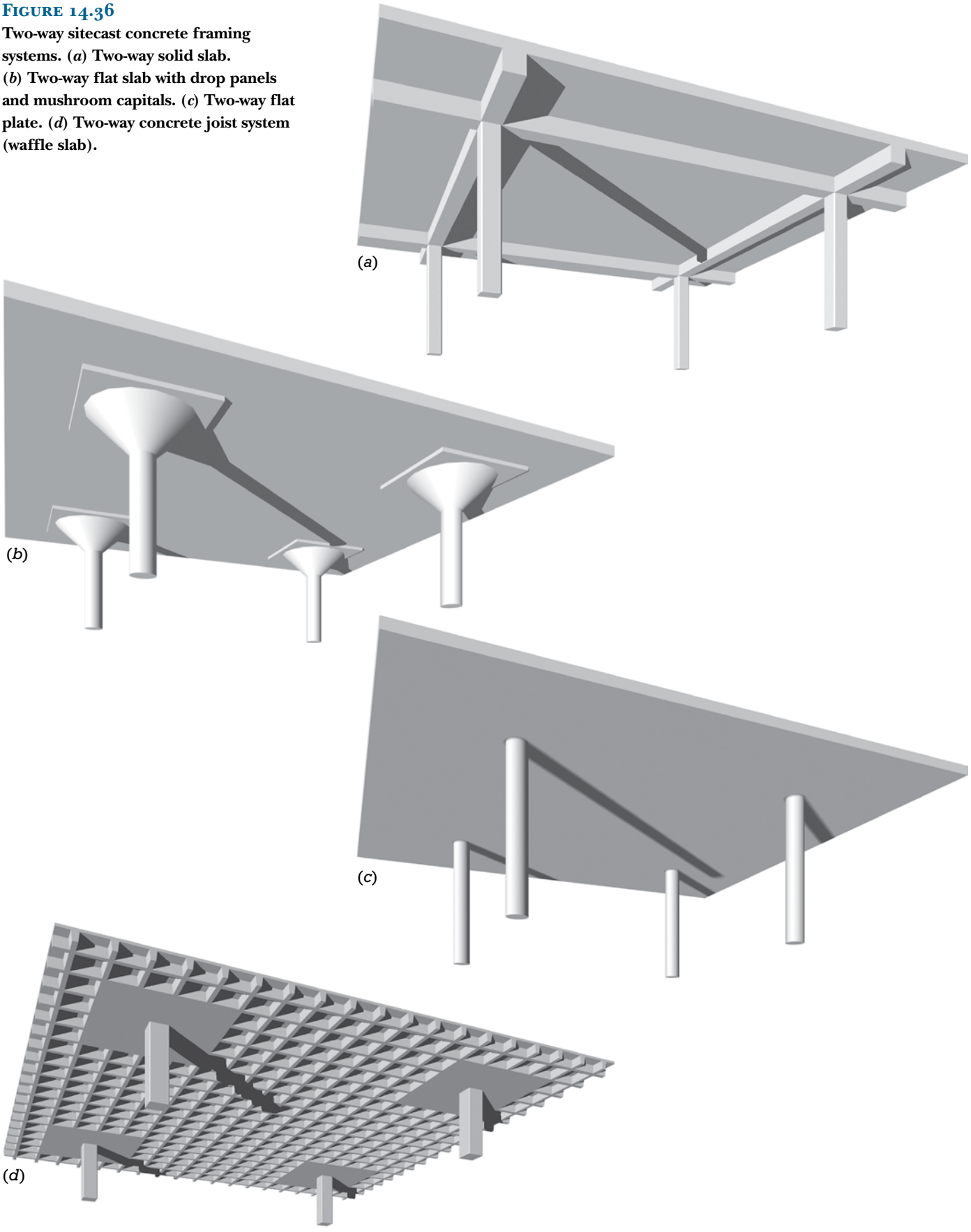
FIGURE 14.35
The underside of a two-way concrete joist floor. Notice how the joists are cantilevered beyond the column line for maximum structural efficiency. *(Courtesy of the Ceco Corporation.)*

joist system. Metal or plastic pans called *domes* are used as formwork to eliminate nonworking concrete from the slab, allowing considerably longer spans than are feasible with the two-way flat plate. Standard domes form joists spaced on 36- to 60-inch (914- to 1524-mm) centers, in depths up to 24 inches (610 mm). Solid concrete *heads* are created around the tops of the columns by leaving the domes out of the formwork in these areas. A head serves the same function as a drop panel in the two-way flat slab system. If a waffle slab cannot be cantilevered at the perimeter of the building, a solid perimeter beam must also be provided. The waffle slab system is suited to longer-span, heavily loaded applications, and its coffered underside presents rich architectural opportunities as an exposed ceiling (Figure 14.35). However, the complexity of waffle slab formwork also makes it the most expensive and least used of sitecast framing systems.

Designing with Two-Way Sitecast Framing Systems

Two-way sitecast framing systems (Figure 14.36) are appropriate where framing bays are roughly square in proportion. For light loads, two-way flat plate is the most economical. Where loads are heavier or lateral force resistance must be developed in the framing system, two-way flat slab is the better choice. Two-way concrete joist is the most expensive of all the sitecast concrete framing systems. However, it can also span the farthest and support heavy floor loads. Combined with its unique architectural character, the two-way joist system still finds occasional usage where its unique advantages justify the high cost.

FIGURE 14.36
Two-way sitecast concrete framing systems. (*a*) Two-way solid slab. (*b*) Two-way flat slab with drop panels and mushroom capitals. (*c*) Two-way flat plate. (*d*) Two-way concrete joist system (waffle slab).



Sitecast Posttensioned Framing Systems

Posttensioning can be applied to any of the sitecast concrete framing systems. It is used in beams, girders, and slabs, both one-way and two-way, to reduce member sizes, reduce deflection, and extend spanning capability.

Two-way flat plate structures are very commonly posttensioned, especially when spans are long or restrictions on the height of the building require minimal slab depths. The tendon layout, however, is quite different from the conventional reinforcing layout shown in Figure 14.30. Instead of being placed identically in both directions, the *draped tendons* are evenly distributed in one direction and banded closely together over the line of columns in the other direction (Figures 14.37 and 14.38). This arrangement functions better structurally in posttensioned slabs because

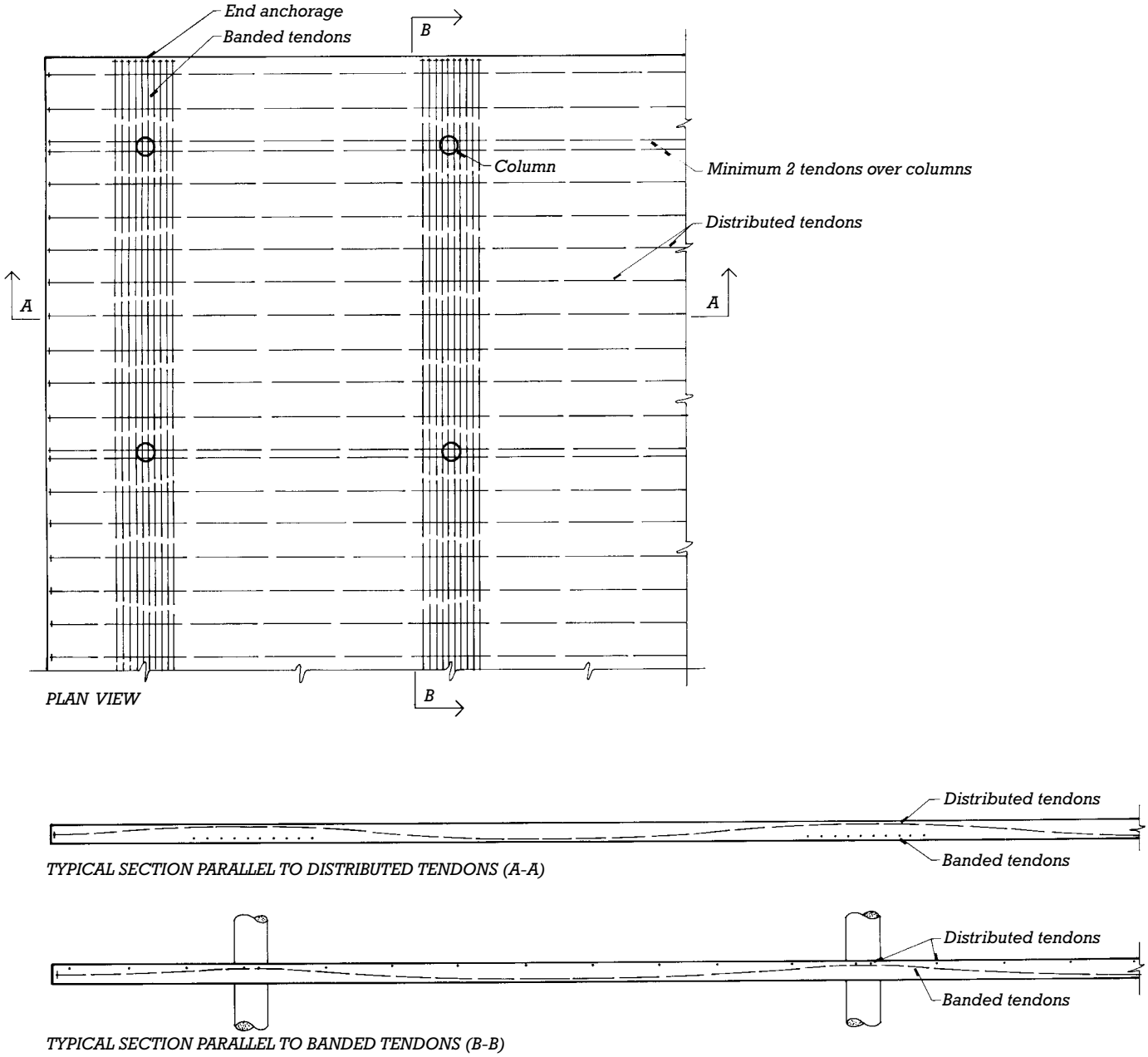


Figure 14.37

A plan and two larger-scale sections of the tendon layout in a two-way flat plate floor with banded posttensioning. The number of tendons running in each of the two directions is identical, but those in one direction are concentrated into bands that run over the tops of the columns. The draping of the tendons is evident in the two section drawings. Building codes require that at least two distributed tendons run directly over each column to help reinforce against shear failure of the slab in this region. In addition to the tendons, conventional steel reinforcing is used around the columns and in midspan, but this has been omitted from these drawings for the sake of clarity.

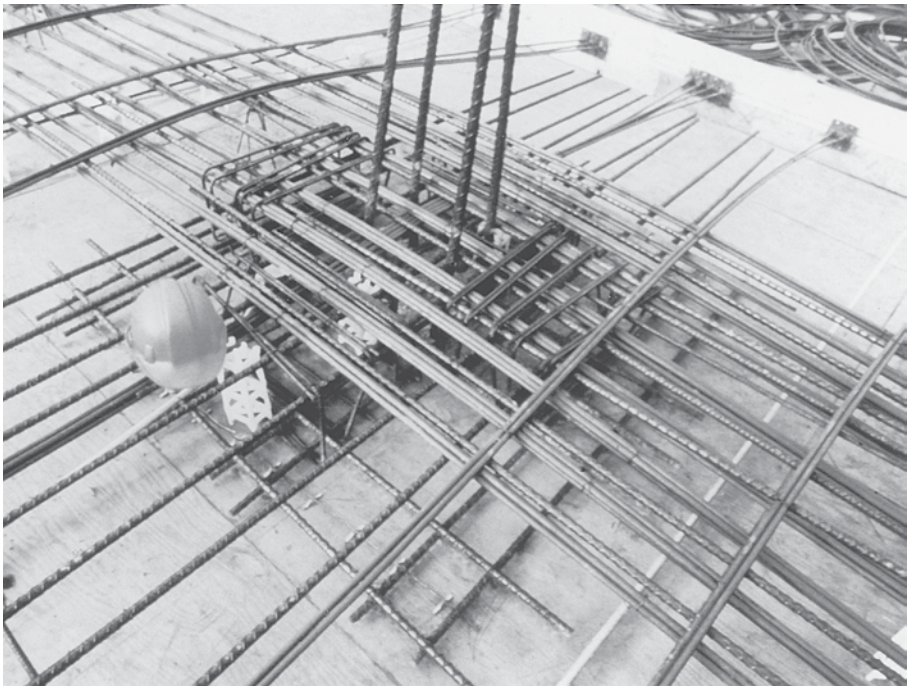


Figure 14.38
Banded tendons run directly through the concrete column of this flat plate floor. A substantial amount of conventional reinforcing is used here for shear reinforcing. Notice the end anchorage plates nailed to the vertical surface of the formwork at the upper right. *(Courtesy of Post-Tensioning Institute.)*

it balances the maximum upward force from the banded tendons against the maximum downward force from the distributed tendons. It is also much easier to install than distributed, draped tendons running in both directions. If the structural bay is square, the same number of tendons is used in each direction. The prestressing force from the banded tendons becomes evenly distributed throughout the width of the slab within a short distance of the end anchorages because of the action of the concrete.

Other Types of Sitecast Concrete

Tilt-Up Construction

In *tilt-up construction*, reinforced concrete wall panels are cast lying down over a previously poured slab that serves as a level, smooth work surface. When the wall panels have cured to sufficient strength, they are lifted up into a vertical orientation and hoisted into position by a crane, then grouted together (Figures 14.39 and 14.54). Tilt-up construction eliminates most of the formwork and formwork costs normally required for sitecast concrete walls, making the system economically favorable for single-story sitecast concrete buildings. Although most tilt-up construction is for walls no taller than 45 feet (14 m), walls approaching heights as great as 100 feet (30 m) are feasible. Tilt-up wall panels can also be cast as sandwich panels with integral rigid plastic insulation to create panels with greater thermal efficiency.

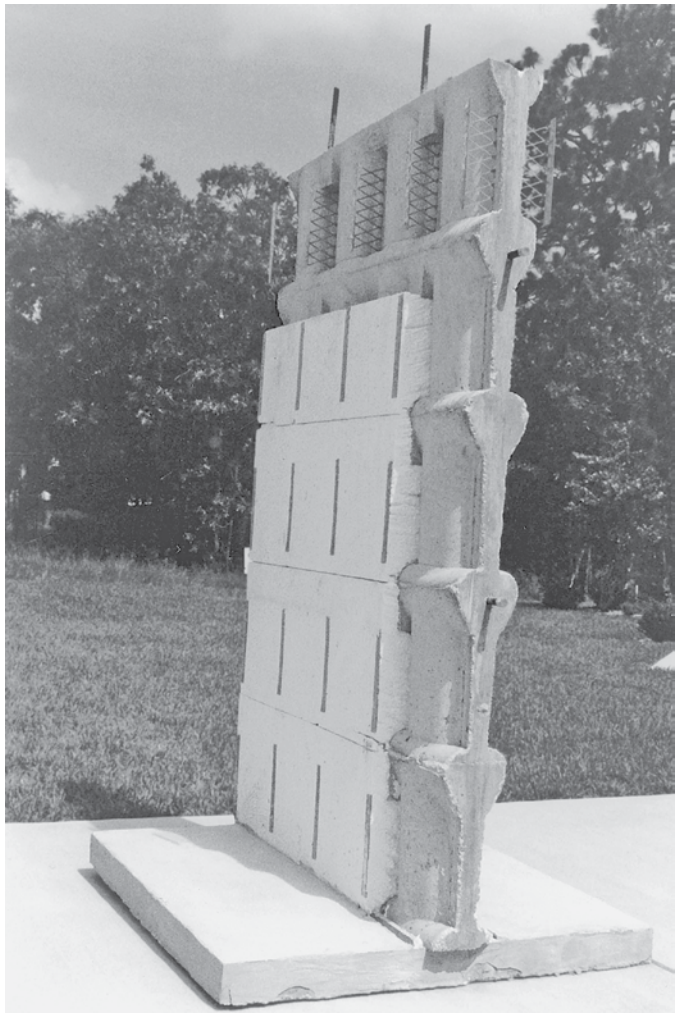
Figure 14.39
Tilt-up construction. The exterior wall panels were reinforced and cast flat on the floor slab. Using special lifting rings that were cast into the panels and a lifting harness that exerts equal force on each of the lifting rings, a crane tilts up each panel and places it upright on a strip foundation at the perimeter of the building. Each erected panel is braced temporarily with diagonal steel struts until the roof structure has been completed. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

Insulating Concrete Forms

Insulating concrete forms (ICFs) serve to contain the concrete when the wall is poured but, unlike conventional formwork, also become a permanent part of the wall, for which they act as thermal insulation (Figure 14.40). The forms are manufactured in differing configurations, such as interlocking hollow blocks of polystyrene foam or foam plastic planks joined with ties to make wall forms.

Insulating concrete forms weigh so little and are so accurately made that they can be assembled almost as easily as building blocks. The form units provide integral support for horizontal reinforcing bars, and vertical bars may also be inserted within the vertical cores. Forms must be braced to prevent them from moving during the concrete pour. Concrete is usually deposited in the cores of the units from the hose of a pump. In cases where the full height of a wall cannot be cast in one operation because the pressure of the wet concrete on the formwork would be too great, concrete is deposited in several *lifts* of lesser height. Each lift only begins after the prior lift has had an hour or two to harden sufficiently to relieve

(*a*)



(*b*)

FIGURE 14.40
Insulating concrete forms are manufactured as interlocking blocks or panels. In the system illustrated here, the inner and outer halves of the blocks are tied together by steel mesh webs that connect to sheet metal strips on the outer surfaces. These strips later serve to receive screws that fasten interior and exterior finish materials to the wall. (*a*) Workers stack the blocks to form the exterior walls of a house. Openings for doors and windows are formed with dimension lumber. Blocks can be cut to length with a simple handsaw. (*b*) This sample wall, from which some of the blocks have been removed, shows that the completed wall contains a continuous core of reinforced concrete with thermal insulation inside and out. *(Courtesy of American Polysteel Forms.)*

pressure in the lower portions of the forms. Interior and exterior finish materials must be applied to the foam plastic faces to protect them from sunlight, mechanical damage, insects, and fire.

Concrete walls constructed with insulating concrete forms have thermal resistance values in the range of R-15 to R-30 (RSI-2.6 to RSI-5.3). ICF walls are also highly resistant to sound transmission, as well as to damage from impact or blast.

Shotcrete

Shotcrete (*pneumatically placed concrete*) is sprayed into place from the nozzle of a hose by a stream of compressed air. Because of its very low slump, even walls with vertical sides can be placed with little in the way of formwork, though some kind of solid surface to spray against is required. Shotcrete is used for foundation walls, stabilization of steep slopes, repairing damaged concrete on the faces of beams and columns, seismic retrofits, and the production of free-form structures such as swimming pools, skate parks, and other play structures.

If we were to train ourselves to draw as we build, from the bottom up . . . stopping our pencil to make a mark at the joints of pouring or erecting, ornament would grow out of our love for the expression of method.

—Louis I. Kahn, quoted in *Louis I. Kahn*, 1962

Architectural Concrete

Most formed concrete surfaces, although structurally sound, also exhibit copious blemishes and irregularities as a regular outcome of standard concrete construction practices. Where sitecast concrete is intended as a quality, finished interior or exterior surface, it can be constructed to higher standards, referred to as *architectural concrete*. Architectural concrete specifications may control flatness and dimensional tolerances, surface textures, uniformity of color, arrangement and appearance of formwork and form-tie artifacts, quantity and size of defects, joint and corner details, and more (Figures 14.41 and 14.42).

Because of its plastic nature, the surface treatment possibilities for sitecast concrete are virtually unlimited (Figure 14.43). *Board form concrete* is created by lining the formwork with rough sawn boards

Figure 14.41
Exposed wall surfaces of sitecast architectural concrete, including board form concrete and concrete sandblasted to expose the aggregate. Formwork panels and form-tie holes spacings are also carefully controlled. *(Architect: Eduardo Catalano. Photo,* **left***, by Erik Leigh Simmons. Photo,* **right***, by Gordon H. Schenck, Jr. Courtesy of the architect.)*

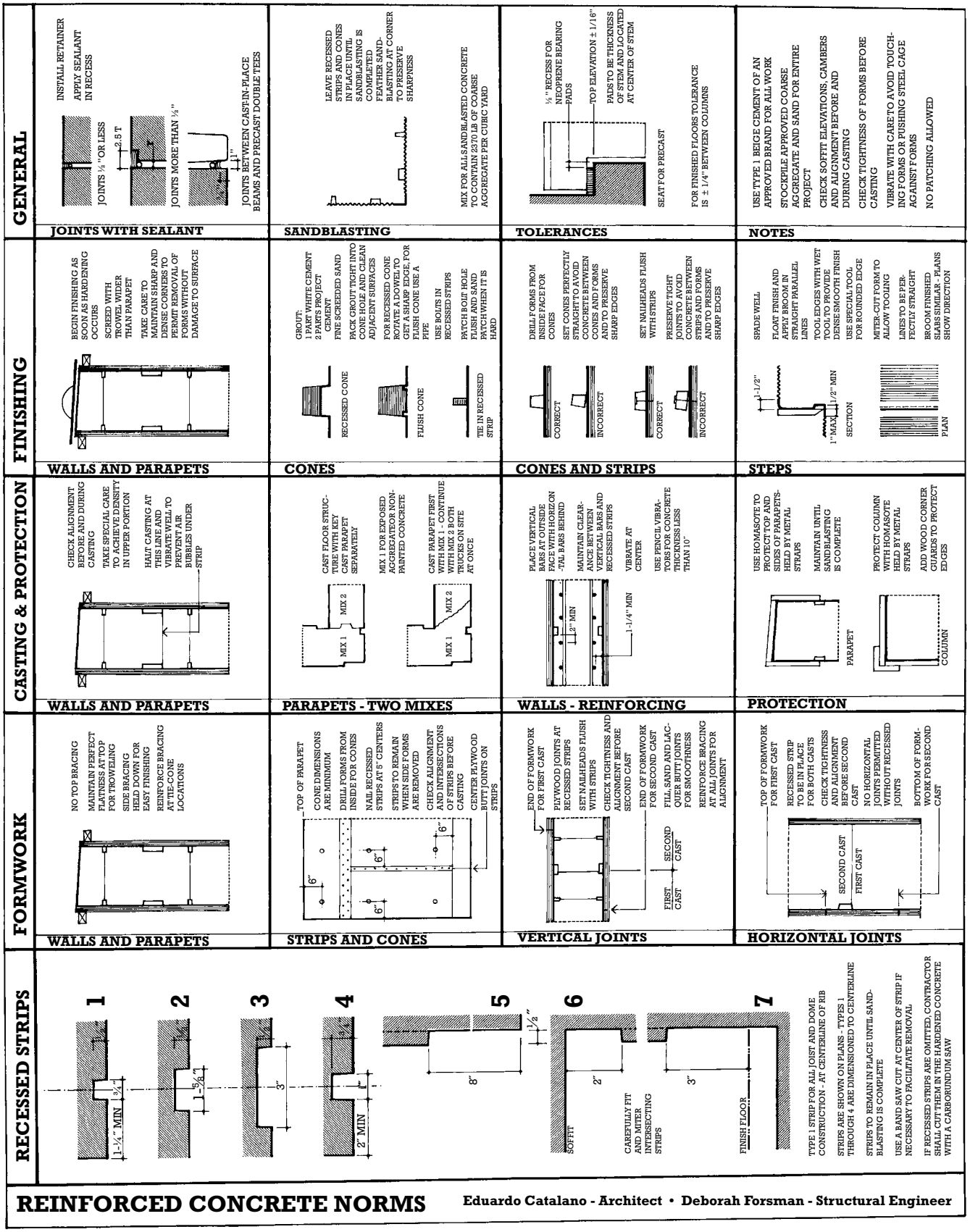


FIGURE 14.42

Standards specified by the architect to control the visual quality of the exposed concrete walls illustrated in Figure 14.41. *(Courtesy of Eduardo Catalano, architect.)*

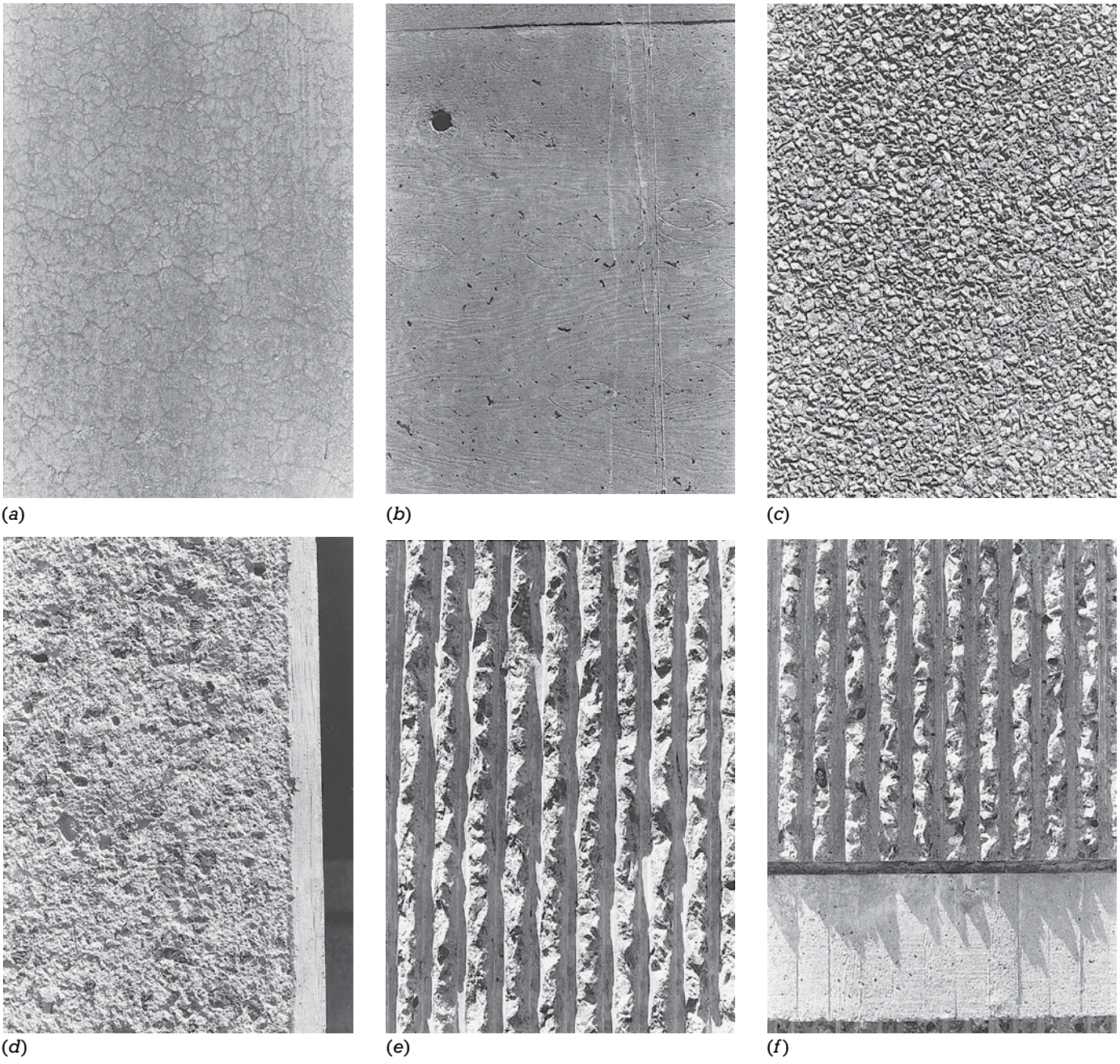


FIGURE 14.43
Examples of surface textures for exposed concrete walls. (*a*) Concrete cast against overlaid plywood to obtain a very smooth surface shows a crazing pattern of hairline cracks after 10 years of service. (*b*) The boat-shaped patches and rotary-sliced grain figure of A-veneered plywood formwork are mirrored faithfully in this surface. A neatly plugged form-tie hole is seen at the upper left, and several lines of overspill from a higher pour have dribbled over the surface. (*c*) This exposed aggregate surface was obtained by coating the formwork with a curing retarder and scrubbing the surface of the concrete with water and a stiff brush after stripping the formwork. (*d*) The bush-hammered surface of this concrete column is framed by a smoothly formed edge. (*e*, *f*) Architect Paul Rudolph developed the techniques of casting concrete walls against ribbed formwork then bush-hammering the ribs to produce a very heavily textured, deeply shadowed surface. In (*f*), the ribbed wall surface is contrasted to a board-formed slab edge, with a recessed rustication strip between. *(Photos by Edward Allen.)*

such that the surface qualities of the boards are imparted into the hardened concrete surface. Other form lining materials can be used to produce textures that range from almost glassy smooth to ribbed, veined, corrugated, or otherwise deeply profiled. After partial curing and removal of the formwork, *exposed aggregate finishes* can be created by scrubbing or hosing of the concrete surface to remove cement paste and reveal the aggregate. Or, the fresh concrete surface can be manipulated by rubbing with abrasive stones, grinding, or hammering with various types of flat, pointed, or toothed masonry hammers. Many types of pigments, dyes, paints, and sealers can be used to add color or gloss to concrete surfaces and to give protection against weather, dirt, and wear.

Pavings, Toppings, and Other Uses

Sitecast concrete finds a variety of other uses in the construction of buildings, such as site pavings and curbs, raised pads for mechanical equipment, toppings over metal or precast concrete decking, fill for the pans of metal stairs, stairs constructed wholly of concrete (Figure 14.44), and other uses.

Basically there are two approaches to the problem of producing a good surface finish on concrete. One is to remove the cement that is the cause of the blemishes and expose the aggregate. The other is to superimpose a pattern or profile that draws attention from the blemishes.

—Henry Cowan, *Science and Building: Structural and Environmental Design in the Nineteenth and Twentieth Centuries*, 1978, p. 283

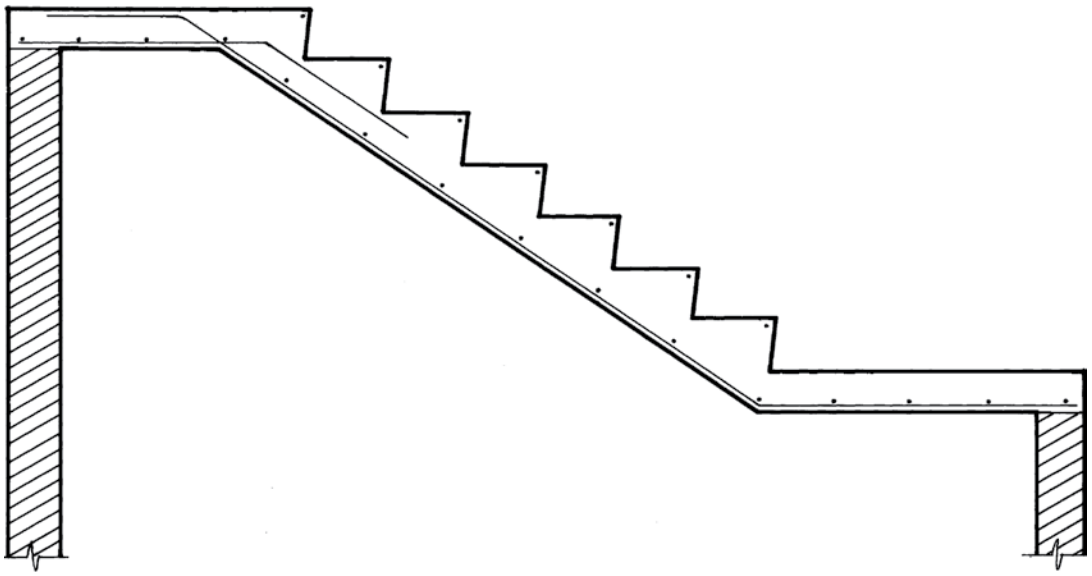


FIGURE 14.44
Section through a simple sitecast concrete stair.

Cutting Concrete, Stone, and Masonry

It is often necessary to cut hard materials, both in the course of obtaining and processing construction materials and during the construction process itself. The quarrying and milling of stone require many cutting operations. Precast concrete elements are frequently cut to length in the factory. Masonry units often have to be cut on the construction site, and masonry walls sometimes require the drilling of fastener holes and cutting of utility openings. Concrete cutting has become an industry in itself because of the need for utility openings, fastener holes, control joints, and surface grinding and texturing. Cutting and drilling are required to create new openings and remove unwanted construction during the renovation of masonry and concrete buildings. Core drilling is used to obtain laboratory test specimens of concrete, masonry, and stone. Cutting is also sometimes necessary to remove incorrect work.

In preindustrial times, hard materials were cut with hand tools, such as steel saws that employed an abrasive slurry of sand and water beneath the blade, and hardened steel drills and chisels that were driven with a heavy hammer. Wedges and explosives in drilled holes were used to split off large blocks of material. These techniques and mechanized variations of them are still used to some extent, but today, diamond cutting tools (Figures A–E) are used for the bulk of the tough cutting chores in the construction industry.

Diamond tools are expensive in first cost. But they cut much more rapidly than other types, they cut more cleanly, and they last much longer, so they are usually more economical overall. Furthermore, diamond tools can do things that conventional tools cannot, such as precision sawing marble and granite into very thin sheets for floor and wall facings. Diamonds cut hard materials efficiently because they are the hardest known material. Most of the industrial diamonds that go into cutting tools are synthetic, produced by subjecting graphite and a catalyst to extreme heat and pressure, then sorting and grading the small diamonds that result.

To manufacture a cutting tool, the diamonds are first embedded in a metallic bonding matrix and the mixture is formed into small cutting segments. The choice of diamonds and the composition of the bonding matrix are governed by the type of material to be cut. The cutting segments are brazed to steel cutting tools—circular saw blades, gangsaw blades, core drill cylinders—and the cutting tools are mounted in the machines that drive them. Some tools are designed to cut dry, but most are used with a spray of water that cools the blade and washes away the waste material. Diamonds are also made into grinding wheels, which are used for everything from sharpening tungsten carbide tools to flattening out-of-level concrete floors and polishing granite.

Cutting tools based on materials other than diamonds are also still common on the construction job site. Tungsten carbide is used for the tips of small-diameter masonry and concrete drills. Low-cost circular saw blades composed of various industrial abrasives are useful for the occasional cutting of concrete and masonry, but the cutting action is slow and the blades wear very quickly. Less precise tools such as the pneumatic jackhammer, hydraulic splitters, and the traditional sledgehammer also have their uses.

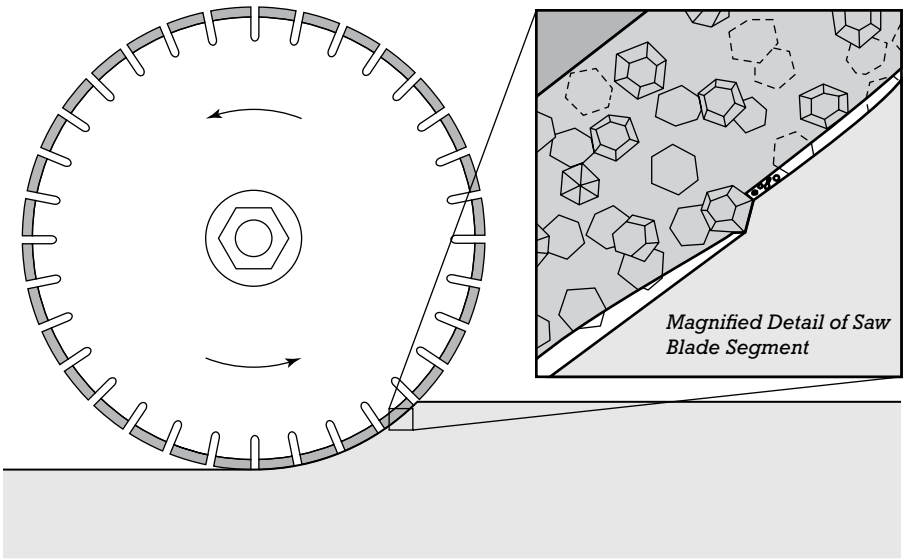


Figure A
A *diamond saw* blade is made up of cutting segments brazed to a steel blade core. Each segment consists of diamond crystals embedded in a metallic bonding matrix. The diamonds in the cutting segment fracture chips from the material being cut. In doing so, each diamond gradually becomes chipped and worn and finally falls out of the matrix altogether. The bonding matrix wears at a corresponding rate, exposing new diamonds to take over for those that have fallen out.

FIGURE B
A hand-held pneumatically powered diamond circular saw cuts excess length from a concrete pile. *(Courtesy of Sinco Products, Inc.)*

FIGURE D
A water-cooled, walk-behind flat saw with circular cutting blade is used to cut pavement. Machines of this type can make cuts in concrete paving and building slabs as deep as 25 inches (635 mm). *(Photo by Joseph Iano.)*

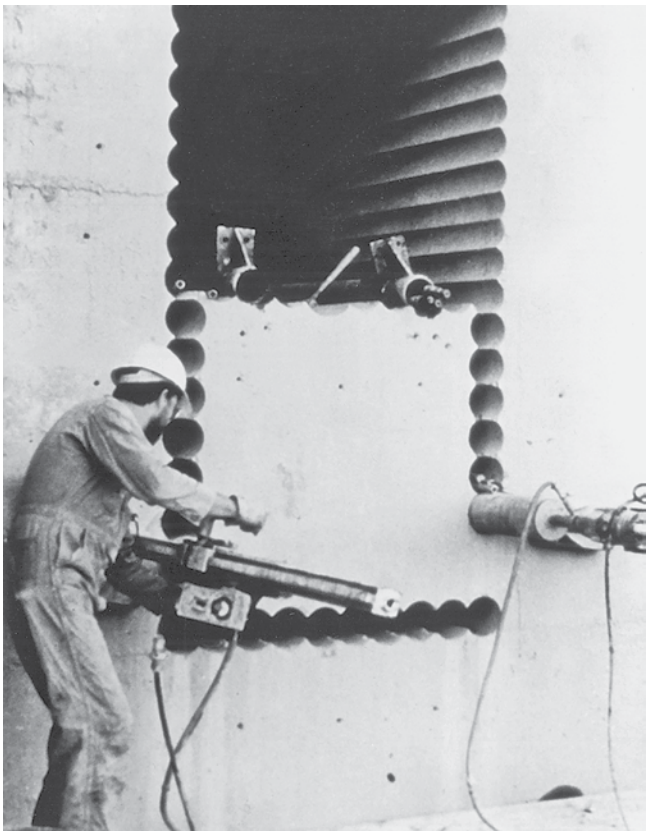


FIGURE C
Using a technique called stitch drilling, a core drill cuts an opening in a very thick concrete wall. *(Courtesy of GE Superabrasives.)*

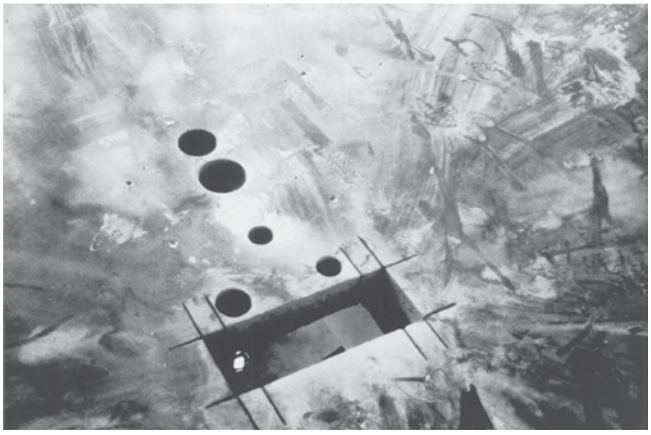


FIGURE E
Sawed and drilled openings for utility lines in a concrete floor slab. *(Courtesy of GE Superabrasives.)*

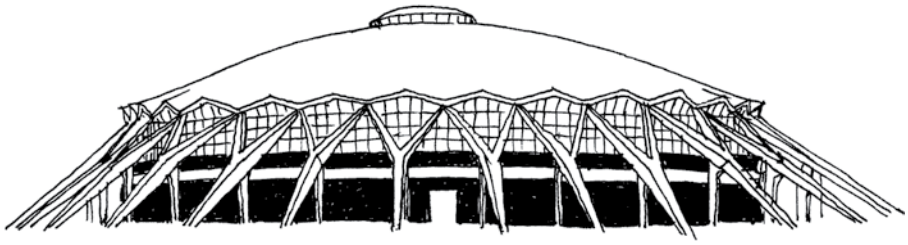
Longer Spans in Sitecast Concrete

The ancient Romans built unreinforced concrete vaults and domes as roofs for temples, baths, palaces, and basilicas. Impressive spans were constructed, including a dome over the Pantheon in Rome, still standing, that approaches 150 feet (45 m) in diameter. Today, the arch, dome, and vault remain appropriate for spanning long distances in concrete because of concrete's suitability to structural forms that work primarily in compression (Figures 14.45 and 14.46*a*). Through folding or scalloping of vaulted forms, or through the use of warped geometries such as the hyperbolic paraboloid, the required resistance to buckling can be achieved with a surprisingly thin layer of concrete, often proportionally thinner than the shell of an egg (Figure 14.46*b*).

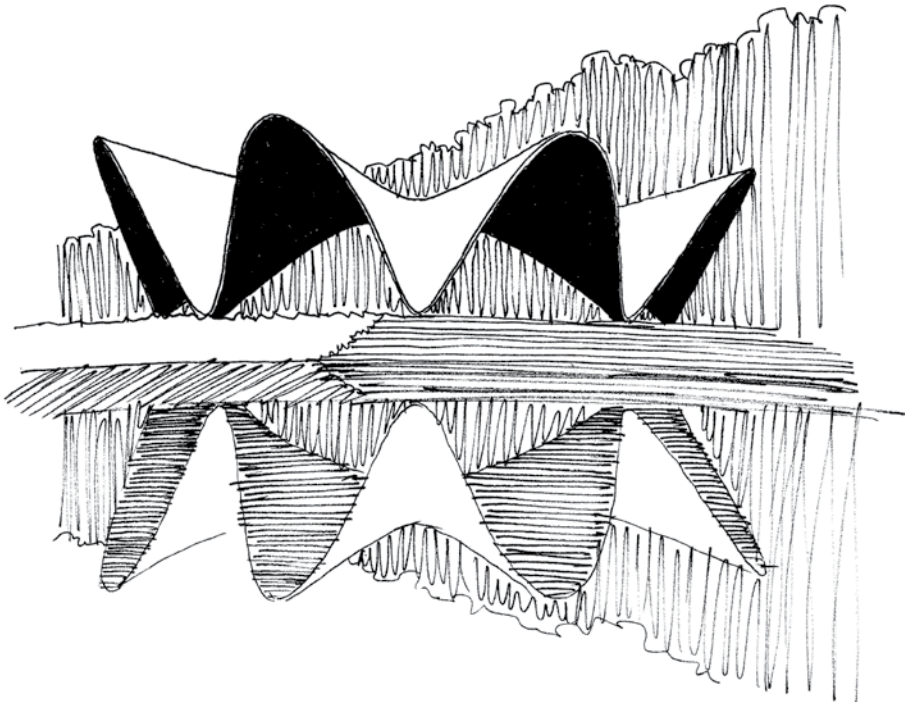
Long-span beams and trusses are possible in concrete, including posttensioned beams and girders and reinforced deep girders analogous to steel plate girders and rigid frames. Concrete trusses and space frames are rare, but possible. (Trusses and space frames include strong tensile forces as well as compressive forces and are heavily dependent on steel reinforcing or prestressing.)

Barrel shells and *folded plates* (Figure 14.46*c*) derive their stiffness and strength from the folding or scalloping of a thin concrete plate to increase its rigidity and structural depth without adding material. Each of these forms depends on reinforcing or posttensioning to resist the tensile forces that it may experience.

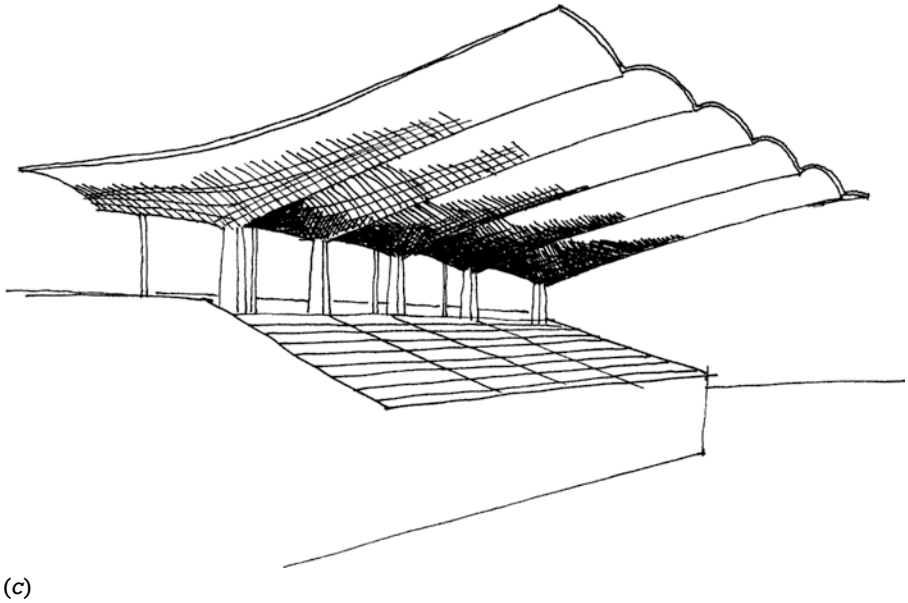
Figure 14.45
The same wooden centering was used four times to form this concrete arch bridge.
(Courtesy of Gang-Nail Systems, Inc.)



(*a*)



(*b*)



(*c*)

FIGURE 14.46
Three concrete shell structures by 20th-century masters of concrete engineering. (*a*) A domed sports arena by Pier Luigi Nervi. (*b*) A lakeside restaurant of hyperbolic paraboloid shells by Felix Candela. (*c*) A racetrack grandstand roofed with cantilevered concrete barrel shells by Eduardo Torroja.

Designing Economical Sitecast Concrete Buildings

The cost of a concrete building frame can be broken down into the costs of the concrete, the reinforcing steel, and the formwork. Of the three, the cost of concrete is usually the least significant in the North American construction market, and the cost of formwork the greatest. In fact, temporary formwork generally accounts for more than half the total cost of conventional sitecast concrete construction.

Accordingly, simplification and standardization of formwork are the first requirements for an economical concrete frame. Repetitive, identical column spacings and bay sizes allow the same formwork to be used again and again without alterations. Flat plate construction is often the most economical, simply because its formwork is so straightforward. Joist band construction is usually more economical than joist construction that uses beams proportioned more efficiently for their structural requirements, because enough is saved on formwork costs to more than compensate for the added concrete and reinforcing steel in the beams. This same reasoning applies if column and beam dimensions are standardized throughout the building, even though loads may vary; the amount of reinforcing and the strengths of the concrete and reinforcing steel can be adjusted to meet the varying structural requirements (Figure 14.47).

Ganged forms (Figure 14.11) for wall construction are large units made up of a number of panels that are supported by the same set of walers. These are handled by cranes and are often more economical than conventional small panels that are maneuvered by hand. For floor slabs, *table-form* (or *flying form*) construction relies on large fabricated formwork sections that are supported on deep metal trusses. The sections are moved from one floor to the next by crane, eliminating much of the labor usually expended on stripping and re-erecting of formwork (Figure 14.48).

Climbing formwork, or *jump form*, construction (Figures 14.32 and 14.49) is used for tall-walled structures such as high-rise building cores, elevator shafts, stairwells, and storage silos. A ring of formwork is supported on previously cast sections of the concrete while workers install reinforcing and pour concrete to cast the next vertical segment of the structure. Once that segment is complete and sufficiently cured, the formwork is lifted to begin again at the next

Figure 14.47
By keeping sizes of columns, beams, and other formed elements as consistent as possible, significant savings can be achieved in the cost of formwork. Here, a column form, having been stripped from a recently cast column, is being moved to a new location for reuse. *(Photo by Joseph Iano.)*

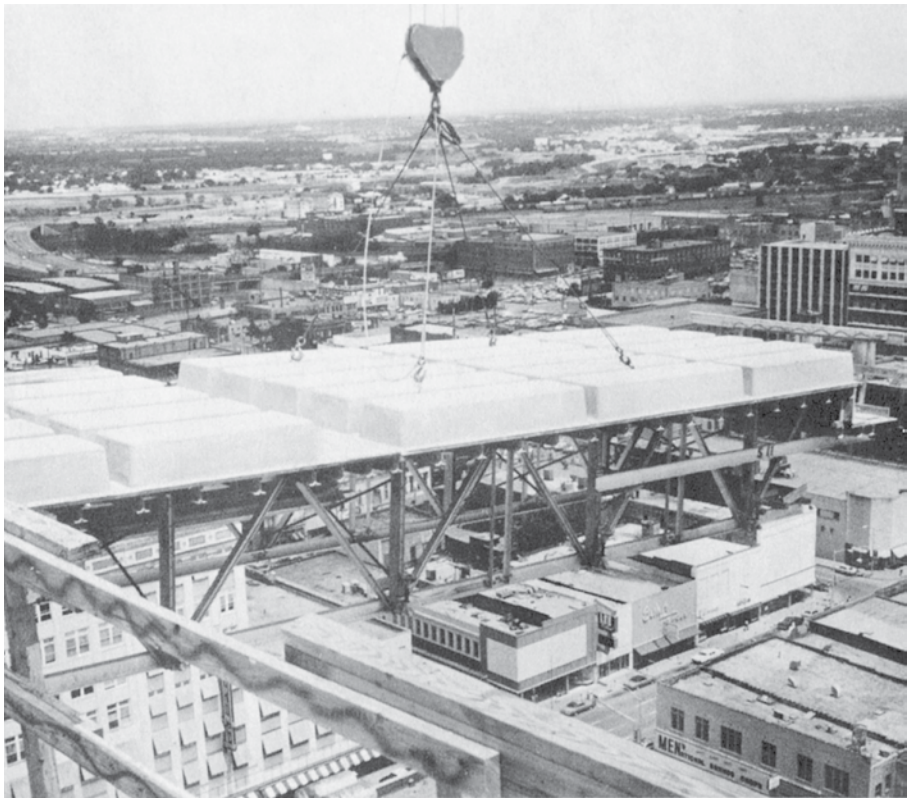
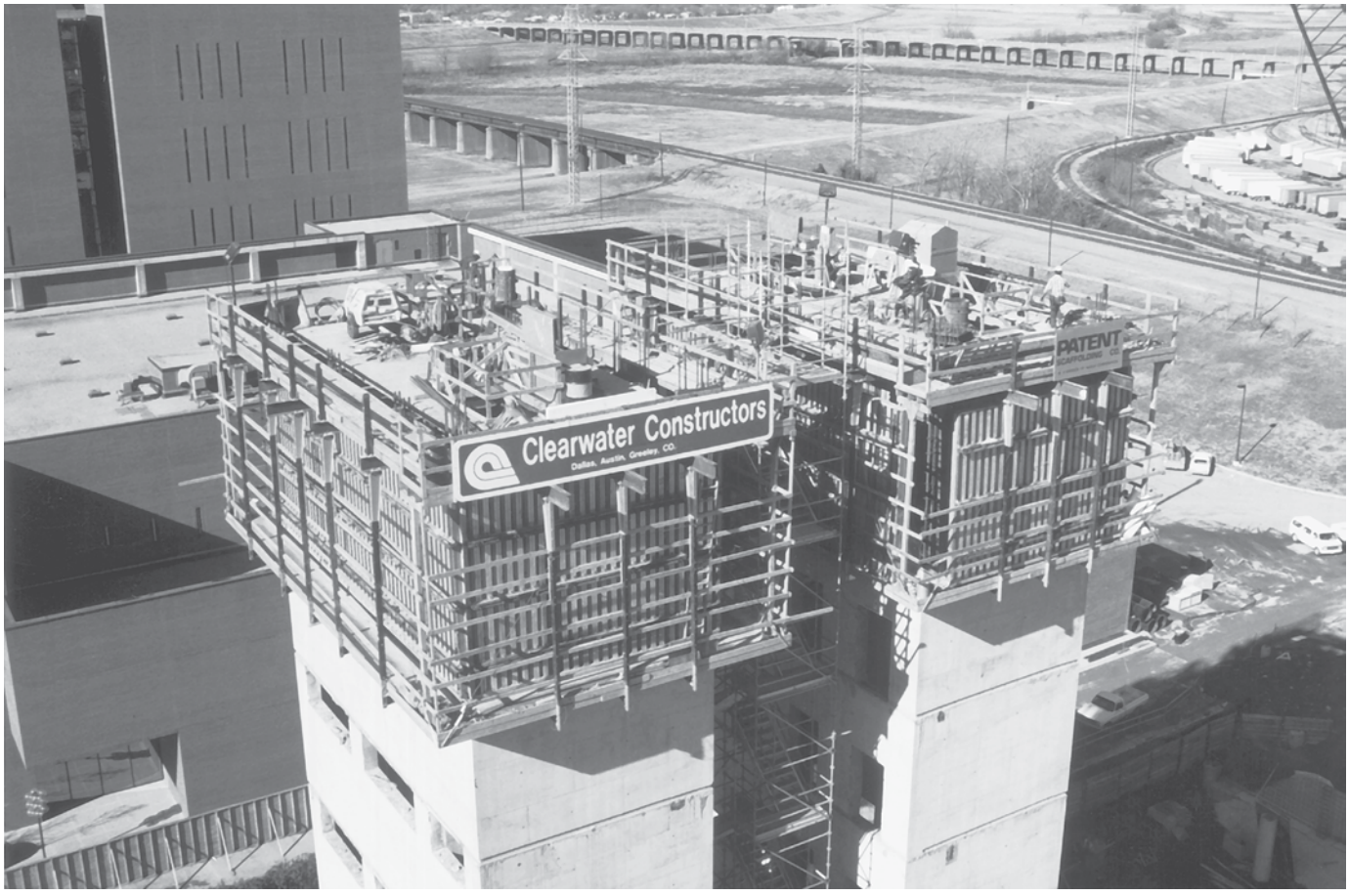


FIGURE 14.48
Flying formwork for a one-way concrete joist system being moved from one floor to the next in preparation for pouring. Stiff metal trusses allow a large area of formwork to be handled by a crane as a single piece. *(Courtesy of Molded Fiber Glass (MFG) Concrete Forms Company.)*

FIGURE 14.49
Self-climbing formwork is being used to cast concrete cores for a tall building. The top level is a working surface from which reinforcing bars are handled and the concrete is poured. The outer panels of the formwork are mounted on overhead tracks just beneath the top level. The panels can be rolled back to the outside of the perimeter walkway after each pour, allowing workers to clean the formwork and install the reinforcing for the next pour. The entire two-story apparatus raises itself a story at a time with built-in hydraulic jacks. *(Courtesy of Patent Scaffolding Company, Fort Lee, NJ.)*



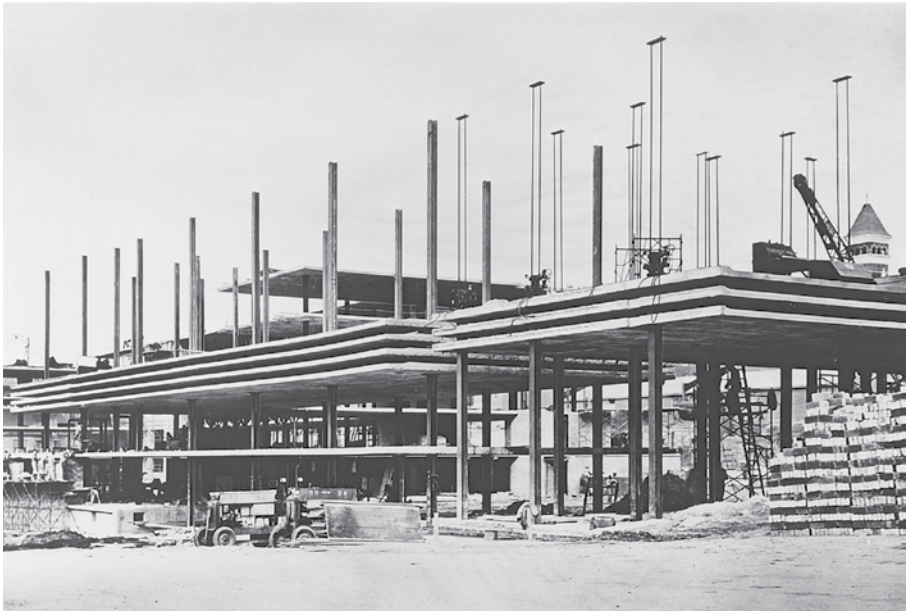


FIGURE 14.50
Lift-slab construction in progress. In North America, this system of construction is no longer used. *(Reprinted with permission of the Portland Cement Association from* **Design and Control of Concrete Mixtures,** *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

PRELIMINARY DESIGN OF SITECAST CONCRETE STRUCTURES

- Estimate the depth of a **one-way solid slab** at 1/12 of its span if it is conventionally reinforced or 1/10 of its span if it is posttensioned. Depths range typically from 4 to 10 inches (100 to 250 mm).
- Estimate the total depth of a **one-way concrete joist system** or **wide-module system** at 1/18 of its span if it is conventionally reinforced or 1/36 of its span if it is posttensioned. To arrive at the total depth, a slab thickness of 3 to 4½ inches (75 to 115 mm) must be added to the depth of the pan that is selected.
- Estimate the depth of **concrete beams** at 1/16 of their span if they are conventionally reinforced or 1/24 of their span if they are posttensioned. For concrete girders, use ratios of 1/12 and 1/20, respectively.
- Estimate the depth of **two-way flat plates** and **flat slabs** at 1/30 of their span if they are conventionally reinforced or 1/45 of their span if they are posttensioned. Typical depths are 5 to 12 inches (125 to 305 mm). The minimum column size for a flat plate is approximately twice the depth of the slab. The width of a drop panel for a flat slab is usually one-third of the span, and the projection of the drop panel below the slab is about one-half the thickness of the slab.
- Estimate the depth of a **waffle slab** at 1/24 of its span if it is conventionally reinforced or 1/35 of its span if it is posttensioned. To arrive at the total depth, a slab thickness of 3 to 4½ inches (75 to 115 mm) must be added to the depth of the dome that is selected.
- To estimate the size of a **concrete column** of normal height, add up the total roof and floor area supported by the column. A 12-inch (300-mm) column can support up to about 2000 square feet (190 m^2) of area, a 16-inch (400-mm) column 4000 square feet (370 m^2), a 20-inch (500-mm) column 6000 square feet (560 m^2), a 24-inch (600-mm) column 9000 square feet (840 m^2), and a 28-inch (700-mm) column 10,500 square feet (980 m^2). These sizes are greatly influenced by the strength of the concrete used and the ratio of reinforcing steel to concrete. Columns are usually round or square.
- To estimate the thickness of a **concrete loadbearing wall**, add up the total width of floor and roof slabs that contribute load to the wall. An 8-inch (200-mm) wall can support approximately 1200 feet (370 m) of slab, a 10-inch (250-mm) wall 1500 feet (460 m), a 12-inch (300-mm) wall 1700 feet (520 m), and a 16-inch (400-mm) wall 2200 feet (670 m). These thicknesses are greatly influenced by the strength of the concrete used and the ratio of reinforcing steel to concrete.

These approximations are valid only for purposes of preliminary building layout and must not be used to select final member sizes. They apply to the normal range of building occupancies, such as residential, office, commercial, and institutional buildings and parking garages. For manufacturing and storage buildings, use somewhat larger members.

For more comprehensive information on preliminary selection and layout of a structural system and sizing of structural members, see Edward Allen and Joseph Iano, *The Architect's Studio Companion* (6th ed.), Hoboken, NJ, John Wiley & Sons, 2017.

higher level. The formwork can be lifted by a construction crane, or it can be self-climbing, raised by hydraulic jacks that are a built-in part of the formwork system. A less common variation on this approach is *slip form* construction, in which the formwork progresses continuously, night and day, at a slow but steady prescribed rate, while construction proceeds within the formwork surrounds.

Other strategies rely on reducing the amount of formwork required for concrete casting. Tilt-up construction and insulating concrete forms are two examples, already discussed, that greatly reduce temporary formwork or eliminate it altogether. *Lift-slab construction* is a system in which floor and roof slabs of a building are cast in a stack on the ground and then jacked up the building columns to their final elevations, where they fixed in place. Though intriguing in concept, this system is no longer practiced in North America, due to a history of past construction accidents (Figure 14.50).

Sitecast Concrete and the Building Codes

Concrete structures are inherently fire-resistant. Under the heat of fire, the concrete water of hydration is gradually driven out and the concrete loses strength. But this deterioration is slow because considerable heat is needed to raise the temperature of the mass of concrete to the point where dehydration begins, and a large additional quantity of heat is required to vaporize the water. Furthermore, the steel reinforcing bars or prestressing strands are buried beneath a concrete cover that protects them for an extended period of time as well. Except under unusual circumstances, such as a prolonged fire fueled by stored petroleum products, concrete structures usually survive fires with little more than cosmetic damage and are repaired with relative ease.

Sitecast concrete is noncombustible and can be used in any building code construction type, as long as it can meet the necessary fire resistance rating requirements. Frequently, the inherent protective qualities of the concrete are sufficient for this purpose. However, in systems with relatively thin slabs, such as joisted construction, slab thickness may need to be increased beyond the structurally necessary minimum, or the underside of the slab may be protected with applied fireproofing materials so as to satisfy requirements for higher levels of fire protection.

Uniqueness of Sitecast Concrete

The continuing evolution of high-strength, high-stiffness concrete, and high-strength reinforcing, along with improvements in concrete forming systems and concrete pumping technology, have enabled sitecast concrete construction to remain economically competitive with structural steel for buildings of virtually any type or size. The Petronas Towers are one such example (Figure 14.51). Another is the 2720-foot (830-m)-tall Burj Khalifa in Dubai, United Arab Emirates, constructed of steel reinforced sitecast concrete for most of its height. Self-consolidating concrete, as strong as 14,500 psi (100 MPa), was used in its construction.

Concrete is a shapeless material that must be given form by the designer. For economy, the designer can adopt a standard system of concrete framing. For excitement, one can invent new shapes and textures. Some have pursued its sculptural possibilities, others its surface patterns and textures, still others its structural logic. From each of these routes have come masterpieces—Le Corbusier's chapel at Ronchamp (Figure 14.52); Wright's Unity Temple (Figure 14.1); and the elegant structures of Torroja, Candela, and Nervi, examples of which are sketched in Figure 14.46. Many of these masterpieces, especially from the latter three designers, were also constructed with impressive economy. Sitecast concrete can do almost anything, be almost anything, at almost any scale, and in any type of building. It is a potent architectural material, and therefore a material both of spectacular architectural achievements and dismal architectural failures. A material that is so malleable demands skill and restraint from those who would build with it, and a material so commonplace requires imagination if it is to rise above the mundane.

Figure 14.51
Concrete work nears the 1475-foot (450-m) summit of the twin Petronas Towers in Kuala Lumpur, Malaysia, which were, at the time of their construction, the world's tallest buildings. Each tower is supported by a perimeter ring of 16 cylindrical concrete columns and a central core structure, also made of concrete. The columns vary in diameter from 8 feet (2400 mm) at the base of the building to 4 feet (1200 mm) at the top. For speed of construction, the floors were framed with steel and composite metal decking. Concrete with strengths as high as 11,600 psi (80 MPa) was used in the columns. The architect was Cesar Pelli & Associates. The structural engineers were Thornton-Tomasetti and Rahnill Bersekutu. The U.S. partner in the joint venture team that constructed the towers was J.A. Jones Construction Co. of Charlotte, North Carolina. *(Photo by Uwe Hausen, J.A. Jones, Inc.)*

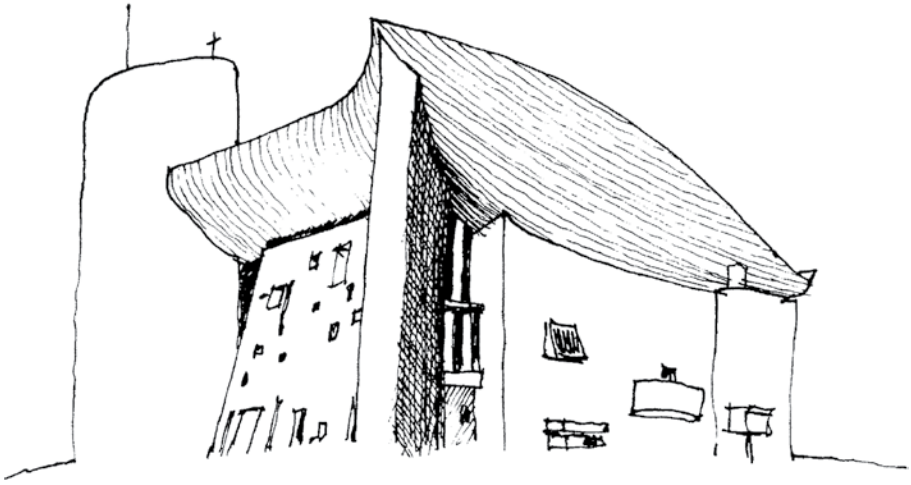


FIGURE 14.52
Le Corbusier's most sculptural building in his favorite material, concrete: the chapel of Notre Dame de Haut at Ronchamp, France (1950–1955).

FIGURE 14.53
The plastered surfaces of Frank Lloyd Wright's Guggenheim Museum (1943–1956) cover a helical ramp of cast-in-place concrete. *(Photo by Wayne Andrews.)*

Figure 14.54
The Chapel of St. Ignatius, Seattle University, designed by architect Steven Holl, is a tilt-up concrete structure. *(Photo by Joseph Iano.)*

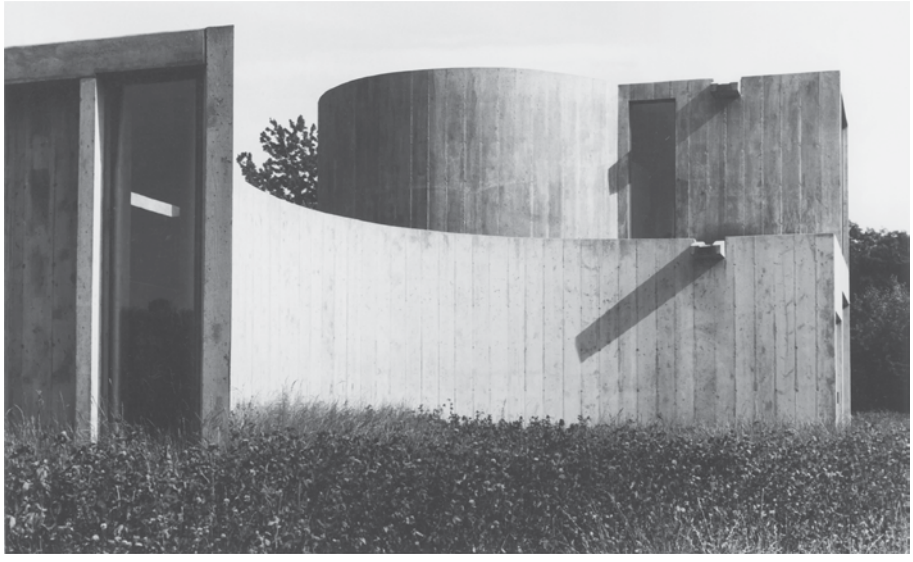


Figure 14.55
A sitecast concrete house in Lincoln, Massachusetts. *(Architects: Mary Otis Stevens and Thomas F. McNulty.)*

Figure 14.56
The TWA Terminal at John F. Kennedy Airport, New York, 1956–1962. *(Architect: Eero Saarinen. Photo by Wayne Andrews.)*

CSI/CSC MasterFormat Sections for Sitecast Concrete Framing Systems

03 31 00	**STRUCTURAL CONCRETE**
03 33 00	**ARCHITECTURAL CONCRETE**
03 35 00	**CONCRETE FINISHING**
03 37 00	**SPECIALTY PLACED CONCRETE**
03 37 14	Shotcrete
03 38 00	**POST-TENSIONED CONCRETE**
03 39 00	**CONCRETE CURING**
03 47 00	**SITE-CAST CONCRETE**
03 47 13	Tilt-Up Concrete
03 47 16	Lift-Slab Concrete
03 80 00	**CONCRETE CUTTING AND BORING**

Key Terms

slab on grade
capillary break
vapor retarder
strike off, screed
floating
bull float
darby
bleed water
troweled slab
steel trowel
rotary power trowel
knee board
broom finish
restraightening
straightedge
shake-on hardener
curing compound
superflat floor
F-number
contraction joint, control joint
isolation joint, expansion joint
shrinkage-compensating cement
key
dowel
form tie
waler
brace
stripped (formwork)
form-tie hole
one-way solid slab
shore
reshoring
slab band
one-way concrete joist system, ribbed slab
pan
distribution rib
joist band
wide-module concrete joist system, skip-joist system
two-way solid slab
two-way flat slab
mushroom capital
drop panel
column strip
middle strip
two-way flat plate
waffle slab, two-way concrete joist system
dome
head
draped tendon
tilt-up construction
insulating concrete form (ICF)
lift
shotcrete, pneumatically placed concrete
architectural concrete
board form concrete
exposed aggregate finish
diamond saw
barrel shell
folded plate
ganged form
table form, flying form
climbing formwork, jump form
slip form
lift-slab construction

Review Questions

1. Draw from memory a detail of a typical slab on grade and list the steps in its production.
2. Why can't the surface of a slab on grade be finished in one operation, instead of waiting for hours before final finishing?
3. What are contraction joints and isolation joints? Explain the purpose and typical locations for each in a concrete slab.
4. List the steps that are followed in forming and pouring a concrete wall.
5. Distinguish one-way concrete framing systems from two-way systems. Are steel and wood framing systems one-way or two-way? Is one-way construction more efficient structurally than two-way construction?
6. List the common one-way and two-way concrete framing systems and indicate the possibilities and limitations of each.
7. Why posttension a concrete structure rather than merely reinforce it?

Exercises

1. Propose a suitable reinforced concrete framing system for each of the following buildings and determine an approximate thickness for each:
   a. An apartment building with a column spacing of about 16 feet (5 m) in each direction
   b. A newsprint warehouse, column spacing 20 feet × 22 feet (6 m × 6.6 m)
   c. An elementary school, column spacing 24 feet × 32 feet (7.3 m × 9.75 m)
   d. A museum, column spacing 36 feet × 36 feet (11 m × 11 m)
   e. A hotel where overall building height must be minimized in order to build as many stories as possible within a municipal height limit
2. Look at several sitecast concrete buildings. Determine the type of framing system used in each and explain why you think it was selected. If possible, talk to the designers of the building and find out if you were right.
3. Observe a concrete building under construction. What is its framing system? Why? What types of forms are used for its columns, beams, and slabs? In what form are the reinforcing bars delivered to the site? How is the concrete mixed? How is it raised and deposited into the forms? How is it consolidated in the forms? How is it cured? Are samples taken for testing? How soon after pouring are the forms stripped? Are the forms reused? How long are the shores kept in place? Keep a diary of your observations over a period of a month or more.

Selected References

See also the references listed in Chapter 13.

American Concrete Institute. *ACI 303R: Guide to Cast-in-Place Architectural Concrete Practice*. Farmington Hills, MI, updated regularly.

This is a comprehensive handbook on how to produce attractive surfaces in concrete.

American Concrete Institute. *ACI 318: Building Code Requirements for Structural Concrete and Commentary*. Farmington Hills, MI, updated regularly.

This booklet establishes the basis for the engineering design and construction of reinforced concrete structures in the United States.

Concrete Reinforcing Steel Institute. *CRSI Design Handbook*. Schaumburg, IL, updated regularly.

Structural engineers working in concrete use this handbook, which is based on the ACI Code, as their major reference. It contains examples of engineering calculation methods and hundreds of pages of tables of standard designs for reinforced concrete structural elements.

Concrete Reinforcing Steel Institute. *Placing Reinforcing Bars*. Schaumburg, IL, updated regularly.

Written as a handbook for those engaged in the business of fabricating and placing reinforcing steel, this small volume is clearly written and illustrated with diagrams and photographs of reinforcing for all the common concrete framing systems.

Hurd, M. K. *Formwork for Concrete* (7th ed.). Farmington Hills, MI, American Concrete Institute, 2005.

Profusely illustrated, this book is the bible of formwork design and construction for sitecast concrete.

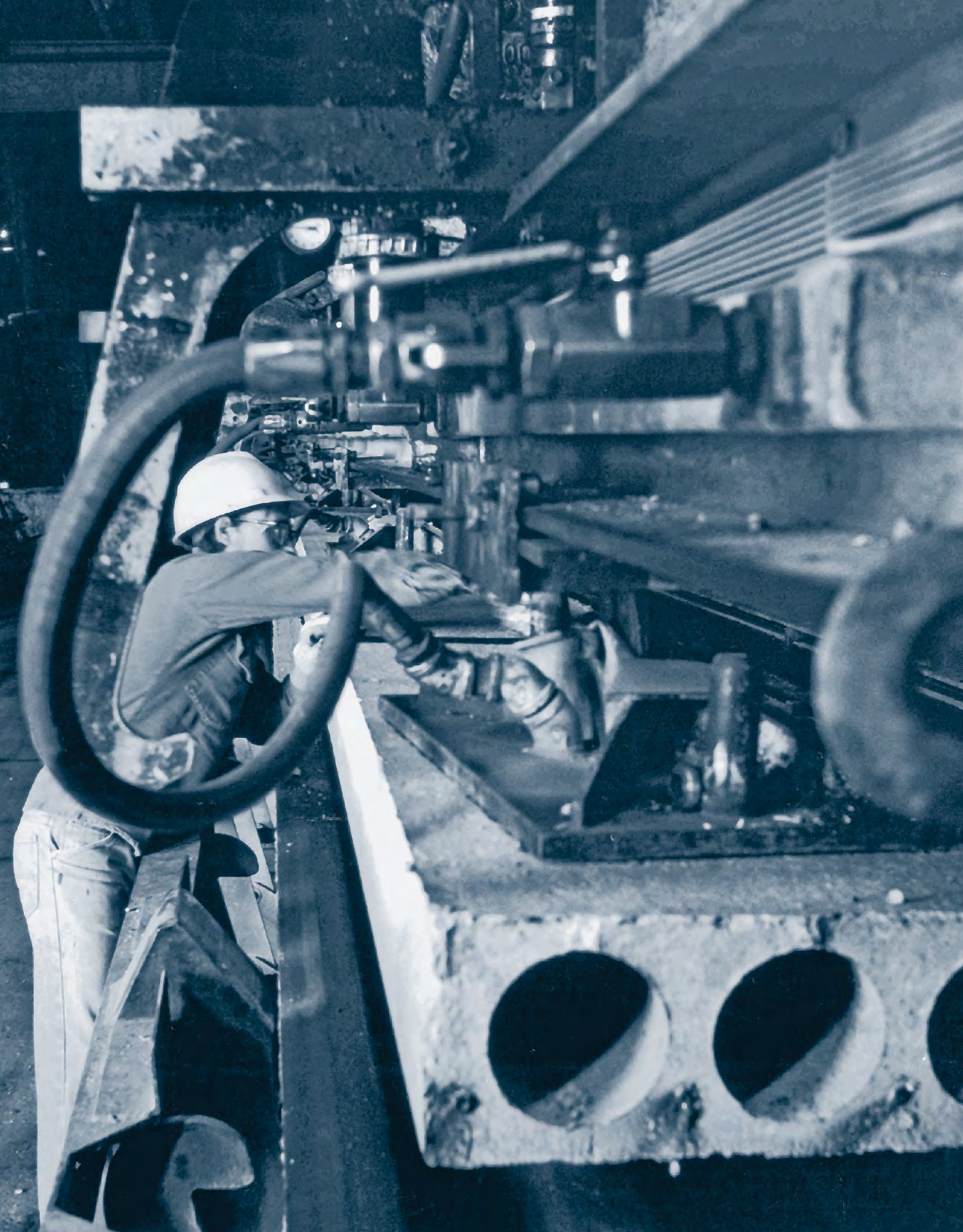
Post-Tensioning Institute. *PTI TAB.1 Post-Tensioning Manual*. Phoenix, AZ, updated regularly.

This heavily illustrated volume is both an excellent introduction to posttensioning for the beginner and a basic engineering manual for the expert.

Websites

Dayton Superior (formwork accessories): www.daytonsuperior.com

Post-Tensioning Institute: www.post-tensioning.org



15

Precast Concrete Framing Systems

- **Precast, Prestressed Concrete Structural Elements**
  - Precast Concrete Slabs
  - Precast Concrete Beams, Girders, and Columns

Preliminary Design of Precast Concrete Structures

  - Precast Concrete Wall Panels
- **Assembly Concepts for Precast Concrete Buildings**
  - Lateral Force Resistance
- **Manufacture of Precast Concrete Structural Elements**
  - Casting Beds
  - Prestressing and Reinforcing Steel
  - Concrete
  - Hollow-Core Slab Production
  - Column Production
- **Joining Precast Concrete Members**

Fastening to Concrete

- **Composite Precast/Sitecast Concrete Construction**
- **The Construction Process**

Sustainability and Precast Concrete Framing Systems

- **Precast Concrete and the Building Codes**
- **Uniqueness of Precast Concrete**

Suction devices lift a precast concrete hollow-core slab from the casting bed where it was manufactured. *(Courtesy of Flexicore Co., Inc.)*

Structural *precast concrete* elements—slabs, beams, girders, columns, and wall panels—are cast and cured in factories, transported to the construction job site in their final form, and erected as rigid components. Precasting concrete offers potential advantages over sitecasting: The production of precast elements is carried out conveniently at ground level. It can be carried out under shelter, or in climate-controlled workspaces. Mixing and pouring operations can be highly mechanized. Workmanship can be higher quality and more consistent than on the construction job site. The concrete is cast in permanent forms made of steel, concrete, glass-fiber-reinforced plastic, or wood panels with smooth overlays, whose excellent surface properties are mirrored in the high-quality surfaces of the finished elements that they produce. The forms may be reused hundreds or thousands of times before they have to be renewed, so formwork costs are low. The forms are equipped to pretension the reinforcing steel in the precast elements. Using steel strands with ultimate strengths as high as 270,000 to 300,000 psi (1860 to 2070 MPa), greater structural efficiencies translate into longer spans, lesser depths, and lower weights compared to conventionally reinforced concrete elements.

To accelerate the curing process, the concrete for precast concrete elements is made with Type III, high early strength portland cement. Once cast, elements may be *steam cured*, furnishing heat to accelerate the hardening of the concrete and moisture for full hydration. Thus, a precasting plant is able to produce cured structural elements, from laying of the prestressing strands to removal of the finished elements from the casting bed, on a 24-hour cycle.

When precast elements are delivered to the construction job site, further advantages are realized: The erection process is similar to that used for structural steel, but it is often faster because most precast concrete systems include precast decking as an integral part of the major spanning elements, eliminating the need for the placing of additional joists or decking components (Figures 15.1 and 15.2). Erection is much faster than with sitecast concrete because there is no formwork to be erected and stripped, and little or no waiting for concrete to cure. Furthermore, erection of precast structures can take place under adverse weather conditions, such as high or low temperatures, which could complicate or delay the sitecasting of concrete.

When the designer is choosing between precast and sitecast concrete, the potential advantages of precasting must be weighed against some potential disadvantages. Precast structural elements, although lighter in weight than similar elements of sitecast concrete, are nevertheless heavy and bulky to transport over roads and hoist into place. This restricts the size and proportions of elements: They can be rather long, but only as wide as the maximum permissible vehicle width of 12 to 14 feet (3.7 to 4.3 m). This restricted width usually precludes utilization of the efficiencies of two-way structural action in precast slabs. Also, the three-dimensional sculptural possibilities of sitecast concrete are largely absent in precast concrete.

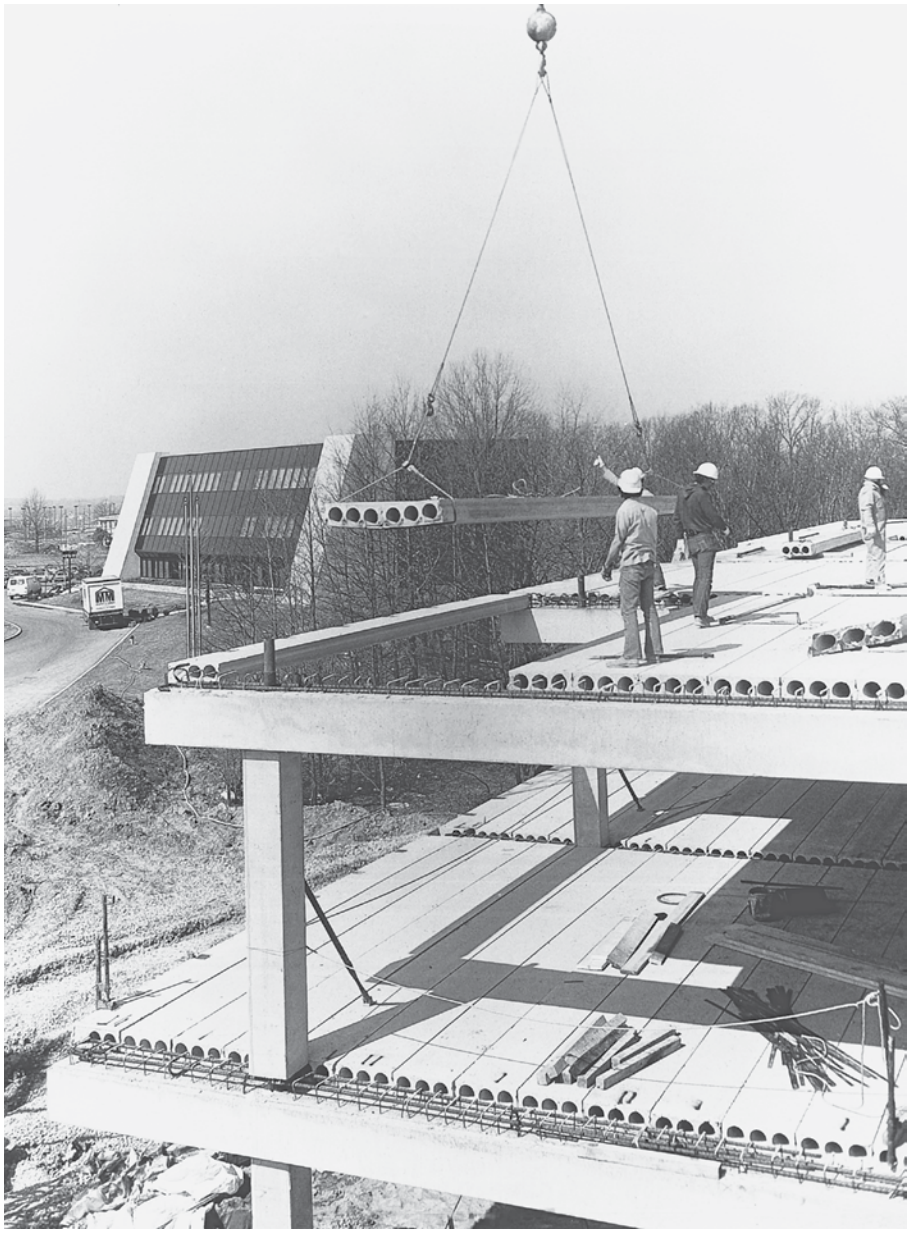


FIGURE 15.1
A precast building frame under construction. A poured concrete topping will cover the hollow-core slabs and the beams to create a smooth floor and tie the precast elements together. *(Courtesy of Flexicore Co., Inc.)*

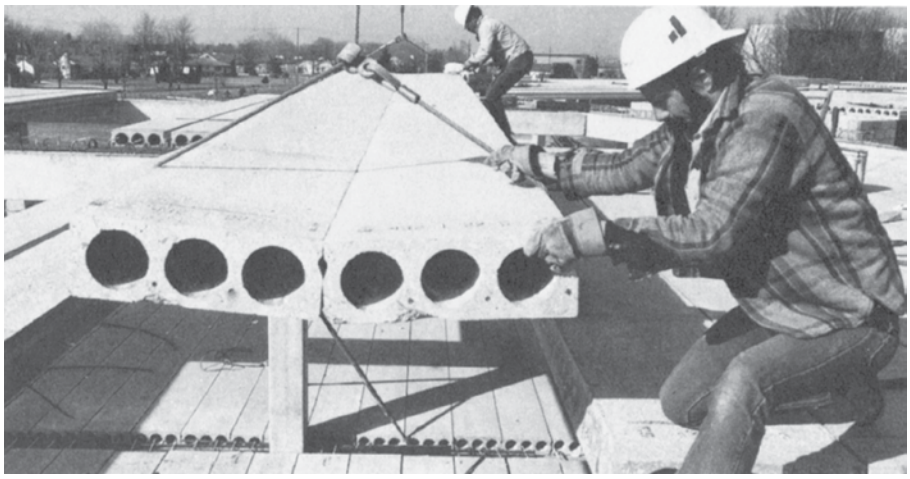


FIGURE 15.2
Workers guide a pair of hollow-core slabs, lowered by a crane in wire rope slings, onto the precast concrete beams that will support them. *(Courtesy of Flexicore Co., Inc.)*

Precast, Prestressed Concrete Structural Elements

Precast Concrete Slabs

The most fully standardized precast concrete elements are those used for making floor and roof slabs (Figure 15.3). For short spans with minimum slab depths, *solid slabs* are appropriate. For longer spans, deeper elements must be used, and precast solid slabs, like their sitecast counterparts, become inefficient because they contain too much deadweight of nonworking concrete. In *hollow-core slabs* (or *hollow plank*), which are precast elements suitable for intermediate spans, internal longitudinal voids replace much of the nonworking concrete. For the longest spans, still deeper elements are required, and *double tees* and *single tees* eliminate still more nonworking concrete.

For most applications, precast slab elements are manufactured with a rough top surface. After they have been erected, a concrete *topping* is poured over them and finished to a flatter, smoother surface. The topping, usually 2 inches (50 mm) thick, bonds during curing to the rough surface of the precast elements and becomes a working part of their structural action. The topping also helps the precast slab elements in resisting concentrated loads and the distribution of lateral forces, and it conceals the slight differences in camber that often occur in prestressed components. Additional reinforcing can be cast in the topping and in-floor electrical conduits may also be embedded. Alternatively, smooth-topped (pre-topped) slabs are sometimes used, eliminating the need for the addition of topping on the construction site, as discussed later in this chapter.

There is considerable overlap in the economical span ranges of the different kinds of precast slab elements, allowing the designer some latitude in choosing which to use in a particular situation. Solid slabs and hollow-core slabs save on overall building height in multistory structures, and their smooth undersides can be painted and used as finish ceilings in many applications. For all but the longest spans, double tees are preferred over single tees because they need not be supported against tipping during erection, simplifying and speeding construction.

Precast Concrete Beams, Girders, and Columns

Precast concrete beams and girders are made in several standard shapes (Figure 15.4). The projecting *ledgers* on *L-shaped beams* and *inverted tees* provide direct support for precast slab elements. They conserve headroom in a building by allowing the beam and slab to share some of the same structural depth. Precast concrete columns are usually square or rectangular in section and may be prestressed or simply reinforced.

Precast Concrete Wall Panels

Precast concrete panels, either prestressed or conventionally reinforced, are used as loadbearing wall panels in many types of low-rise and high-rise buildings. Solid panels range from 3½ to 10 inches (90 to 250 mm) in thickness and can span one or two stories in height. When prestressed, strands are located in the vertical midplane of the wall panels to strengthen

SOLID FLAT SLAB	HOLLOW-CORE SLAB	DOUBLE TEE	SINGLE TEE
Widths vary	2', 4', 8' wide (610, 1220, 2440 mm) (1'–4", 3'–4" some manufacturers)	8', 10" wide (2440, 3050 mm)	8', 10' wide (2440, 3050 mm)

Figure 15.3
Four types of precast concrete slab elements.

Preliminary Design of Precast Concrete Structures

- Estimate the depth of a **precast solid slab** at 1/40 of its span. Depths typically range from 3½ to 8 inches (90 to 200 mm).
- An 8-inch (200-mm) precast hollow-core slab can span approximately 25 feet (7.6 m), a 10-inch (250-mm) slab 32 feet (9.8 m), and a 12-inch (300-mm) slab 40 feet (12 m).
- Estimate the depth of **precast concrete double tees** at 1/28 of their span. The most common depths of double tees are 12, 14, 16, 18, 20, 24, and 32 inches (300, 350, 400, 460, 510, 610, and 815 mm). Some manufacturers can provide double tees that are 48 inches (1220 mm) deep.
- A precast concrete single tee 36 inches (915 mm) deep spans approximately 85 feet (926 m) and a 48-inch (1220-mm) tee 105 feet (32 m).
- Estimate the depth of **precast concrete beams and girders** at 1/15 of their span for light loadings and 1/15 of their span for heavy loadings. These ratios apply to rectangular, inverted-tee, and L-shaped beams. The width of a beam or girder is usually about one-half of its depth. The projecting ledgers on inverted-tee and L-shaped beams are usually 6 inches (150 mm) wide and 12 inches (300 mm) deep.
- To estimate the size of a **precast concrete column**, add up the total roof and floor area supported by the column. A 10-inch (250-mm) column can support up to about 2300 square feet (215 m^2) of area, a 12-inch (300-mm) column 3000 square feet (280 m^2), a 16-inch (400-mm) column 5000 square feet (465 m^2), and a 24-inch (600-mm) column 9000 square feet (835 m^2).

These values may be interpolated to columns in 2-inch (50-mm) increments. Columns are usually square. These approximations are valid only for purposes of preliminary building layout and must not be used to select final member sizes. They apply to the normal range of building occupancies, such as residential, office, commercial, and institutional buildings and parking garages.

For manufacturing and storage buildings, use somewhat larger members. For more comprehensive information on preliminary selection and layout of structural system and sizing of structural members, see Edward Allen and Joseph Iano, *The Architect's Studio Companion* (6th ed.), Hoboken, NJ, John Wiley & Sons, 2017.

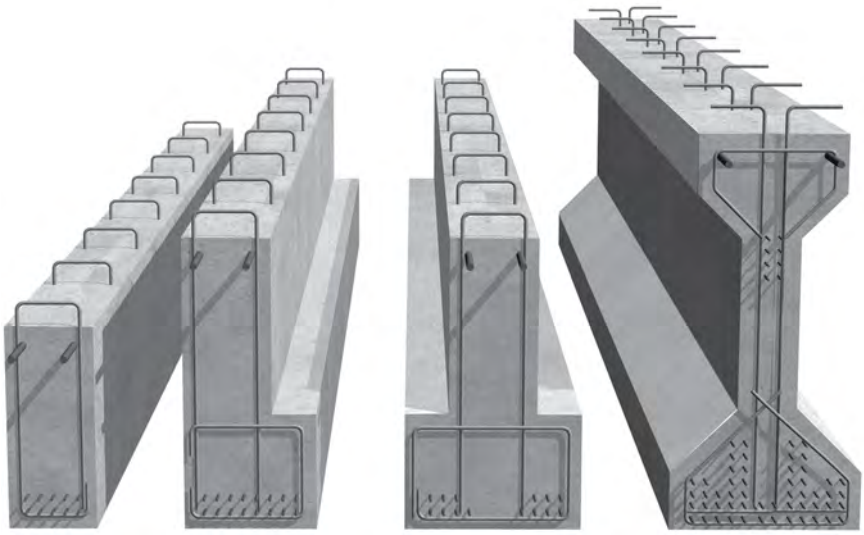


Figure 15.4
Precast concrete beam and girder shapes. The heavier bars near the tops of the beams are mild steel reinforcing, and the smaller strands near the bottom are high-strength prestressing. Mild steel stirrups are also shown. Stirrups usually project above the top of the beam, as shown, to bond to a sitecast concrete topping, creating composite structural action. AASHTO (American Association of State Highway and Transportation Officials) beams were designed originally as efficient shapes for bridge structures. They have also found occasional use in parking garage structures or other utilitarian building types.

the panels against buckling and to avoid camber. Ribbed or hollow-core panels, or sandwich panels with integral rigid foam insulation, may be as deep as 12 to 24 inches (305 to 610 mm) and can span up to four stories (Figure 15.12).

Precast concrete wall panels are also manufactured for residential foundation construction. Vertical ribs, so-called concrete studs, spaced at 24 inches (610 mm), provide faces with sheet metal or wood strips for the attachment of interior finishes and create cavity space that can accommodate insulation or the routing of services. Some manufacturers integrate rigid foam insulation or reinforced footings into the design of the panels.

Long, slender foundation piles, earth-retaining sheet piles, stairs, stadium risers, and even whole walls or rooms are also produced in precast concrete. Nonloadbearing precast concrete wall panels, called *architectural precast concrete*, are discussed in Chapter 20.

Assembly Concepts for Precast Concrete Buildings

Figure 15.5 shows a building whose precast slab elements (double tees in this example) are supported on a skeleton frame of L-shaped precast girders and precast columns. The slab elements in Figure 15.6 are supported on precast loadbearing wall panels. Figure 15.7 illustrates a building whose slabs are supported on a combination of wall panels and girders. These three fundamental ways of supporting precast slabs—on a precast concrete skeleton, on precast loadbearing wall panels, and on a combination of the two—occur in endless variations in buildings. The skeleton may be one bay or many bays deep; the loadbearing walls are often constructed of reinforced masonry or of various configurations of precast concrete; the slab elements may be solid, hollow core, or double tee, topped or untopped. One of the principal virtues of precast concrete as a structural material is that it is locally manufactured to order and is easily customized to an individual building design, usually at minimal additional cost.

Lateral Force Resistance

Precast concrete building structures can rely on any of the lateral force resisting strategies previously discussed for steel frame construction: that is, shear walls, braced frames, and moment-resisting frames (see Chapter 11). Precast concrete elements themselves can be designed to act as shear walls, or with special attention to the design of the connections between parts, as moment-resisting frames. Lateral force resistance can also be provided by other systems, such as sitecast concrete shear walls or structural steel braced frames.

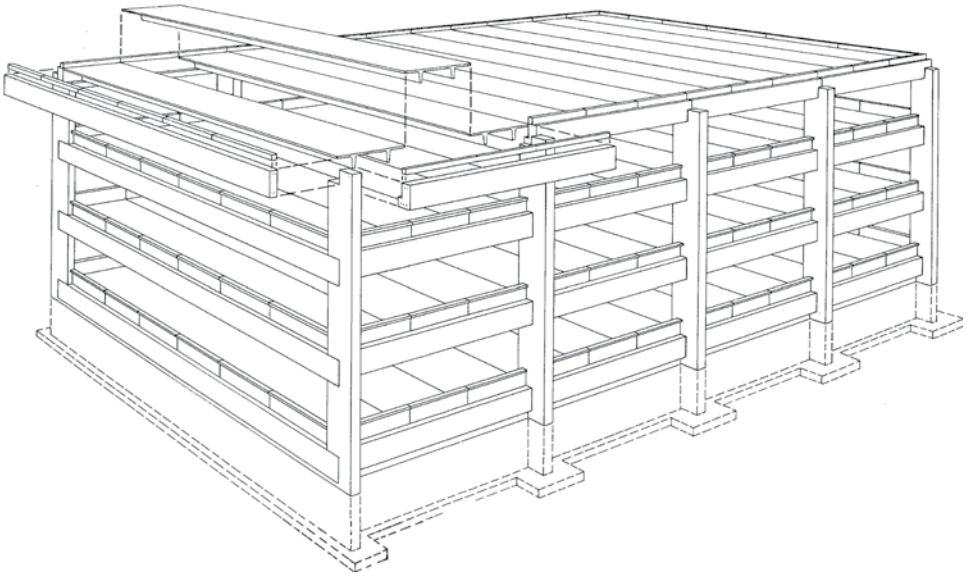


Figure 15.5
Double tees supported on a frame of precast columns and L-shaped girders. *(Courtesy of Precast/Prestressed Concrete Institute.)*

Interactive Exercise

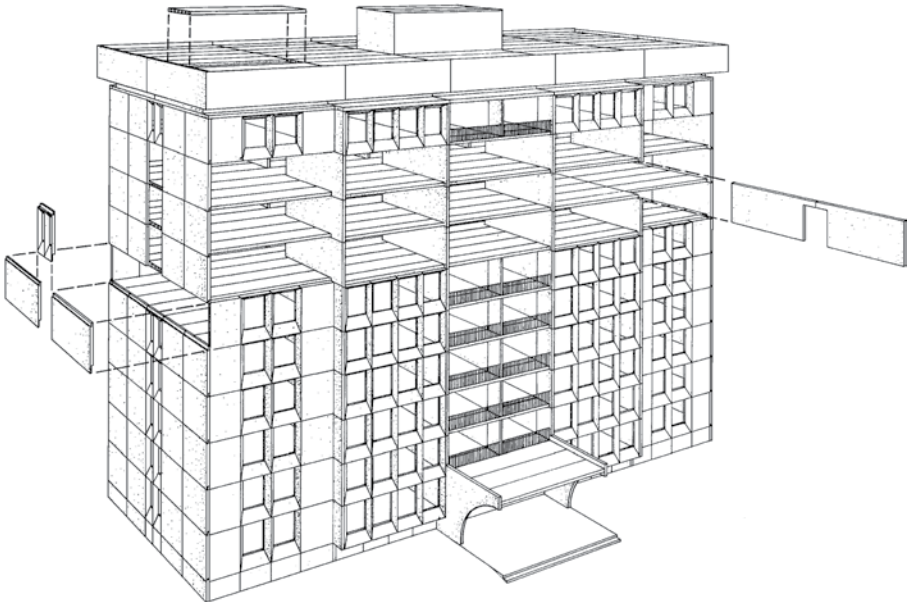


Figure 15.6
Hollow-core slabs supported on precast loadbearing wall panels. *(Courtesy of Precast/Prestressed Concrete Institute.)*

Manufacture of Precast Concrete Structural Elements

Casting Beds

Most precast concrete elements are produced in permanent forms called *casting beds*. Casting beds average 400 feet (125 m) in length but extend 800 feet (250 m) or more in some plants (Figure 15.8). A cycle of

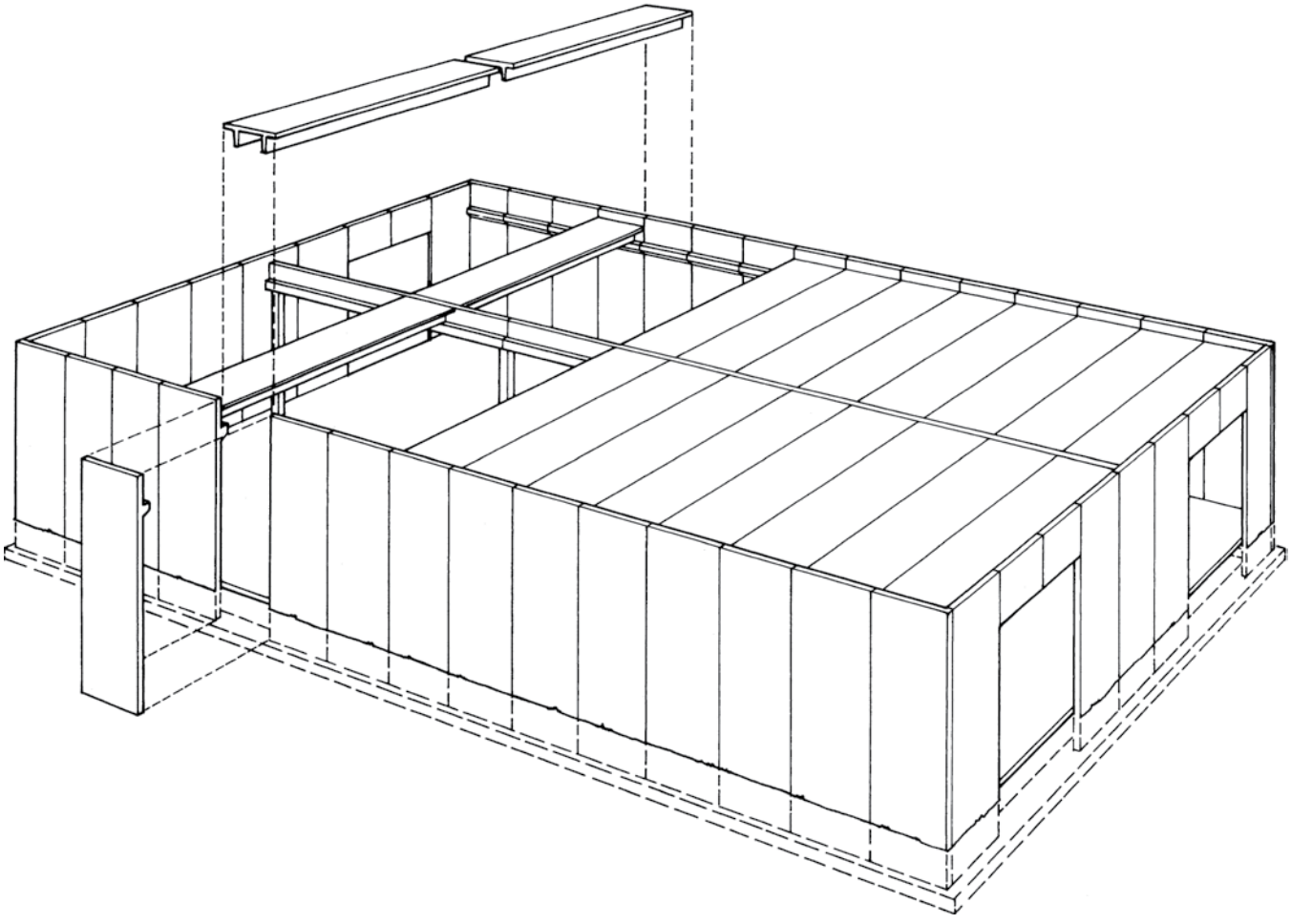
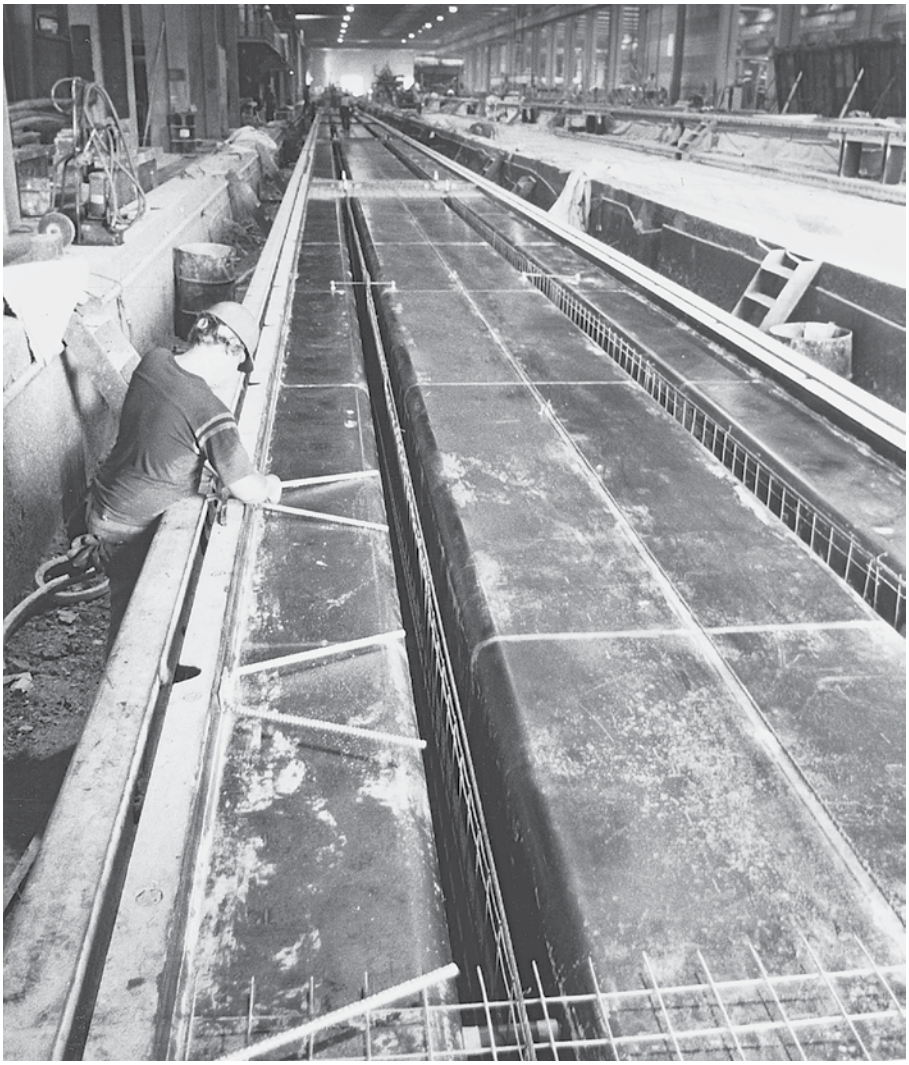
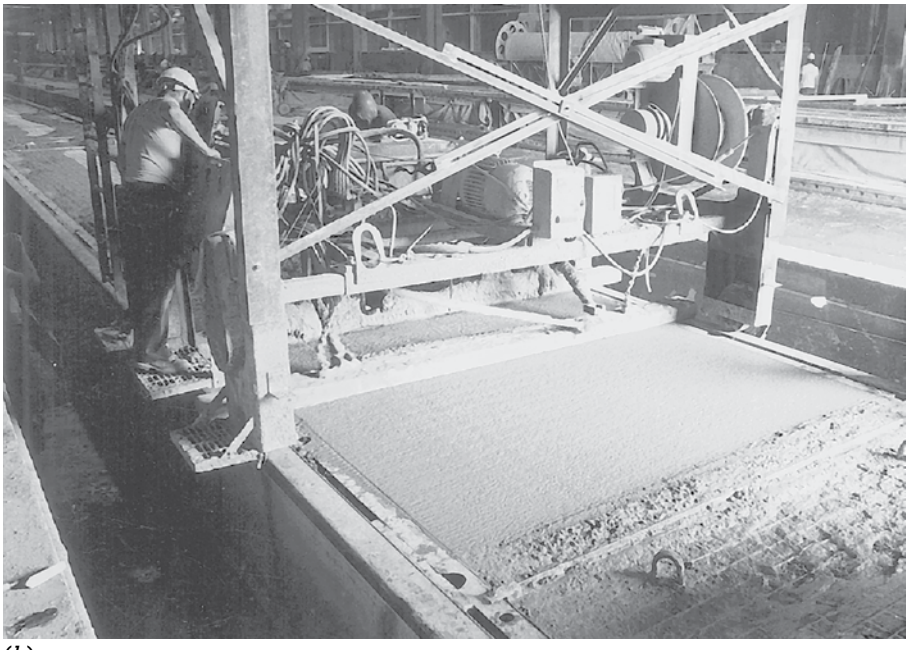


Figure 15.7
Double tees supported on exterior precast loadbearing wall panels and an interior precast columns and inverted-tee beams.
(Courtesy of Precast/Prestressed Concrete Institute.)

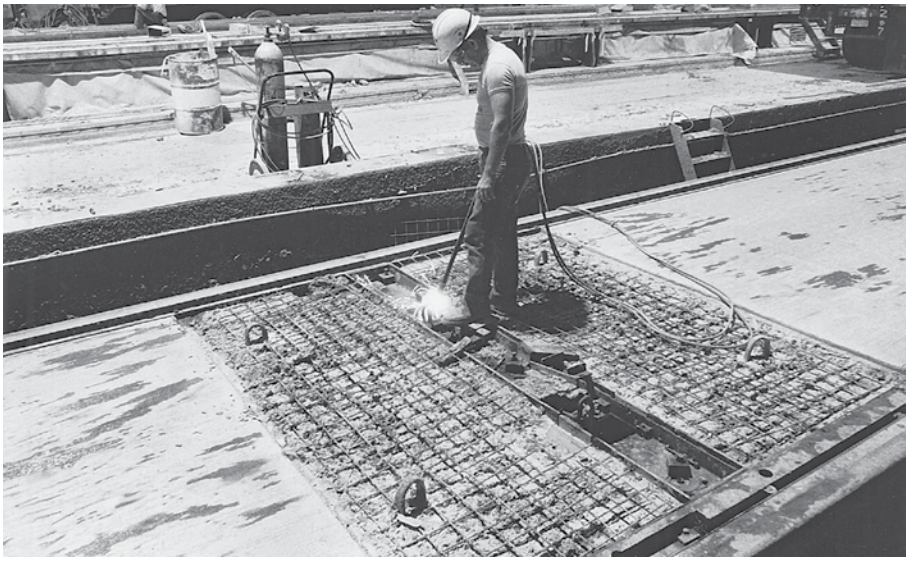


(*a*)

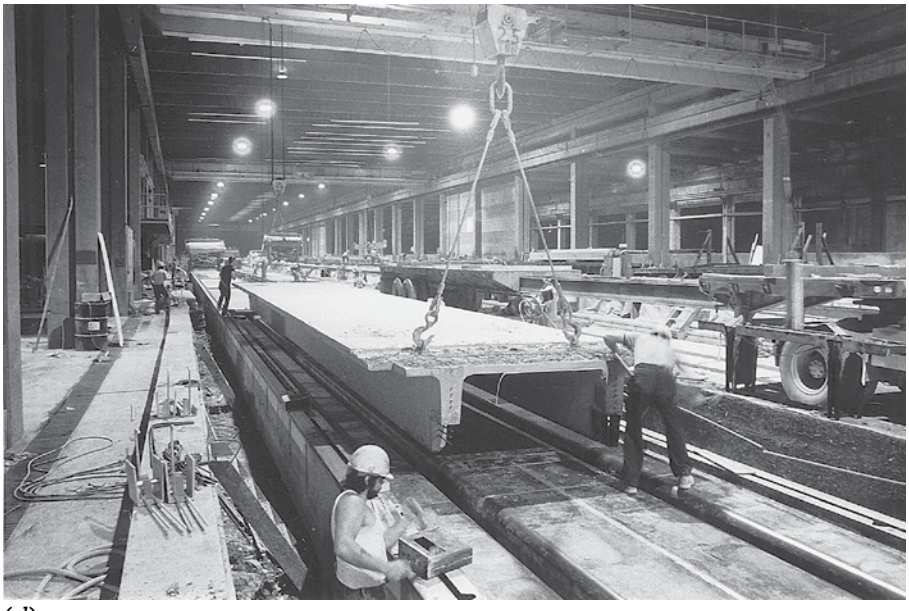


(*b*)

FIGURE 15.8
Manufacturing double tees. (*a*) A worker inserts weld plates with their V-shaped anchors of reinforcing bar in the casting bed prior to the concrete pour. The prestressing strands and welded wire shear reinforcement have been installed in the stems of the double tees, and a portion of the welded wire fabric for the top slab can be seen in the foreground. Notice the great length of the casting bed; many elements are cast end-to-end at the same time. (*b*) The top surface of the concrete is straightedged by machine. (*c*) The next morning, following overnight steam curing, a worker cuts the prestressing strands between bulkhead separators with an oxyacetylene cutting torch. The welded wire fabric is exposed at the ends of the elements because they will be used as untopped slabs (see Figure 15.20). (*d*) Using lifting loops cast into the ends, the slabs are lifted from the bed and stockpiled outdoors. The dapped stems will rest on inverted-tee and L-shaped girders; the notched corner will fit around a column. (*e*) Loading the double tees for trucking. *(Photos by Alvin Ericson.)*



(*c*)



(*d*)

(*e*)

precasting usually begins in the morning, as soon as the elements that were cast the previous day have been lifted from the beds. High-strength steel reinforcing strands are strung between the abutments at the extreme ends of the bed. The strands are pretensioned with hydraulic jacks, during which process they stretch considerably. Once the strands are fully tensioned, transverse bulkhead separators may be placed along the bed at the required intervals to divide the individual elements from one another. Or, for solid slabs, cored slabs, and wall panels, the bulkheads are often omitted; the cured slab or panel is simply sawed into the required lengths before it is removed from the bed.

When pretensioning and separator placement have been completed, mild steel reinforcing bars and welded wire fabric are placed as required. *Weld plates*, for attachments to be completed later in the field, and other embedments are installed. Then the concrete is placed in the bed, vibrated to eliminate voids, and struck off level. If the slabs are to be used without topping, the top surface is finished further with floats and trowels. Live steam or radiant heat and moisture are then applied to the concrete to accelerate its curing. Ten to twelve hours after pouring, the concrete has reached a compressive strength of 2500 to 4000 psi (24 to 28 MPa) and has bonded to the steel strands. The next morning, after the strength of the concrete has been verified by testing cylinders in the laboratory, the exposed strands are cut between the bulkhead separators, releasing the external force in the strands, which spring back to prestress the concrete. Asymmetrically prestressed slab and beam elements immediately arch up from the casting bed to take on a pronounced camber as the prestressing force is released into them. When the elements have been separated from one another, they are hoisted off the bed and stockpiled, ready for shipment. Then a new cycle of casting begins.

Prestressing and Reinforcing Steel

Solid slabs, hollow-core slabs, and wall panels are cast around horizontal strands. Tees, double tees, beams, and girders are often cast around depressed or harped strands for greater structural efficiency (Figures 13.43 and 15.9).

Ordinary mild steel reinforcing is also cast into prestressed concrete elements for various purposes: Beams or slabs that will cantilever beyond their supports are given top reinforcing bars over the cantilever points. Welded wire reinforcement is used to reinforce the flanges of tees and double tees and for general reinforcing of wall panels. Where stirrups are required in the stems of beams and single or double tees, they are made of either mild steel reinforcing bars or welded wire reinforcement (Figure 15.10). Additional reinforcing may be installed to add strength around *dapped* (notched) *ends* and openings in panels or slabs for pipes, ducts, columns, and hatchways. Weld plates and other metal connecting devices are cast into the elements as required. Projecting steel loops are cast into many types of elements as crane attachments for lifting.

Carbon Fiber Reinforcing

Carbon fiber reinforcing may be substituted for mild steel reinforcing in precast concrete elements, such as for shear stirrups and temperature steel in slabs, single and double tees, and wall panels. Because carbon fiber does not require protection from corrosion, less concrete cover is required than for steel reinforcing. This can result in thinner, lighter-weight reinforced components. The low thermal conductivity of carbon fiber, combined with the thinner concrete sections possible, allows the production of insulated panels with better thermal performance. The higher tensile strength and stiffness of carbon fiber in comparison to mild steel, and the innovative ways in which grids of carbon fiber reinforcing can be integrated into precast concrete components, can yield improvements in structural efficiency as well.

Concrete

Concrete for precast concrete elements is formulated and manufactured in the same way as sitecast concrete. Mixes with 28-day strengths from 4000 to 6000 psi (28 to 41 MPa) are most common. These more quickly achieve the minimum strength required to allow removal of the cast units from the formwork than would be possible with lower strength mixes. Higher-strength mixes may be used, for example, for structural columns to reduce column size and gain usable floor area, or for foundation piles. Some slab elements are manufactured with lightweight concrete, approximately 20 percent less dense than normal concrete. This reduces loads on the frame and foundations. Self-consolidating

FIGURE 15.9
A precasting bed being readied for the pouring of a long AASHTO girder. Side forms for the mold can be seen in the background to the right. The depressed strands are held down in the center of the beam by steel pulleys that will be left in the concrete after pouring. The bed is long enough that several girders are being cast end-to-end, with the depressed strands pulled up and down as required. Mild steel reinforcing bars are used for stirrups. The projecting tops of the stirrups will bond to the sitecast topping. Vertical twists of prestressing strand near the end of the girder will serve as lifting loops. *(Courtesy of Blakeslee Prestress, Inc.)*

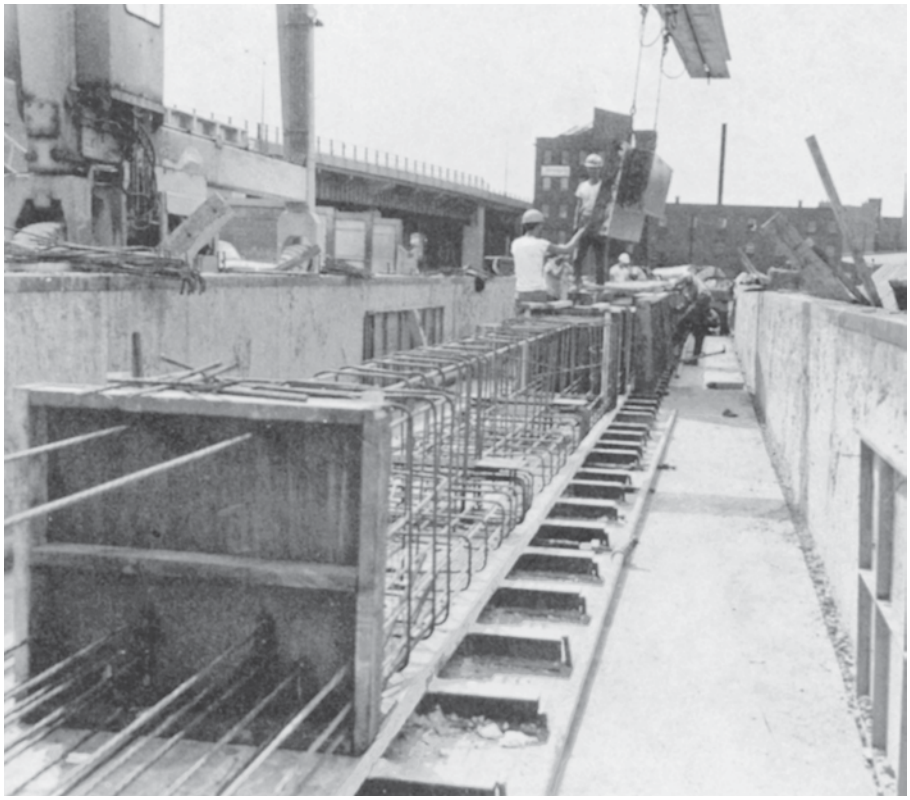


FIGURE 15.10
Workers install side forms for inverted-tee beams in an outdoor casting bed. Mild steel reinforcing bars are used extensively for stirrups. *(Courtesy of Blakeslee Prestress, Inc.)*

concrete, described in Chapter 13, can be used to increase casting productivity and produce a higher finish quality product.

Precast concrete is manufactured and constructed to the same standards as sitecast concrete, that is ACI 318 and ACI 301 (see Chapter 13), and additional standards promulgated by the precast concrete industry that relate to the unique aspects of this manufacturing process.

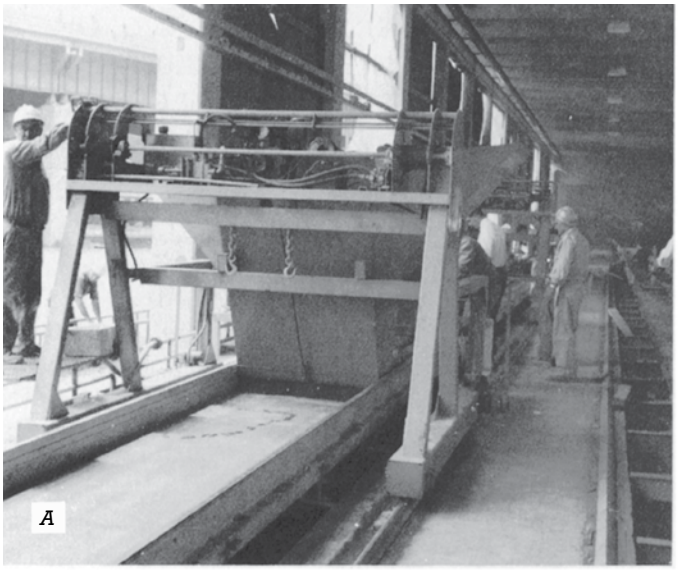
Hollow-Core Slab Production

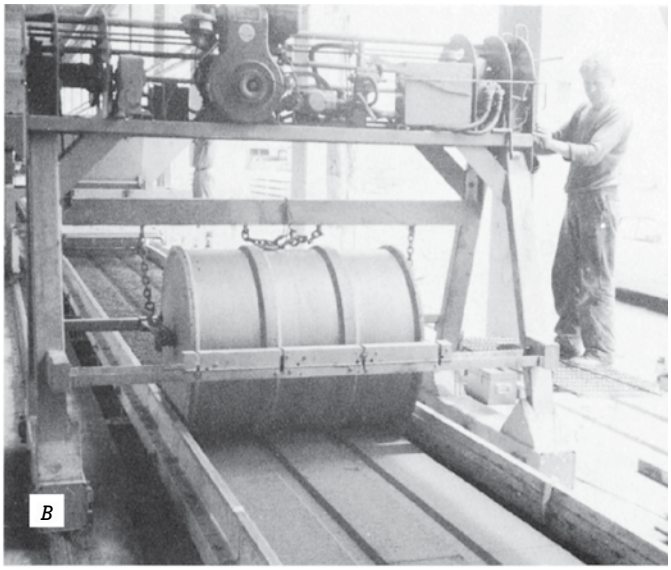
The longitudinal voids in hollow-core slabs can be formed by a number of processes. In the *extruded process*, devices squeeze an extremely dry, stiff concrete mix through a moving die, not unlike squeezing toothpaste from a toothpaste tube, to produce the voided shape directly. This method has the disadvantage that vertical openings and weld plates must be added after the concrete is extruded. Openings are cut out of the stiff but still wet concrete just after extrusion or sawed after curing (Figure 15.11). Weld plates are added by hand before the concrete has completely cured. In the *wet-cast process*, a bottom layer of wet concrete is deposited in the casting bed. Then a second layer of concrete is placed, with collapsible tubes or lightweight aggregate carefully positioned to form the voids. Embed plates and forms to create openings in the slab are set prior to casting. The tubes or aggregate are removed after the concrete has cured. In the *slip-form process*, a moving hopper deposits a zero-slump concrete mix in the casting bed. Tubes that form the slab cores move with the hopper and are pulled out of the slab as the casting process proceeds from one end of the slab to the other. This process falls somewhere between the wet-cast and extrusion processes in terms of the relative ease of placing embeds and forming openings.

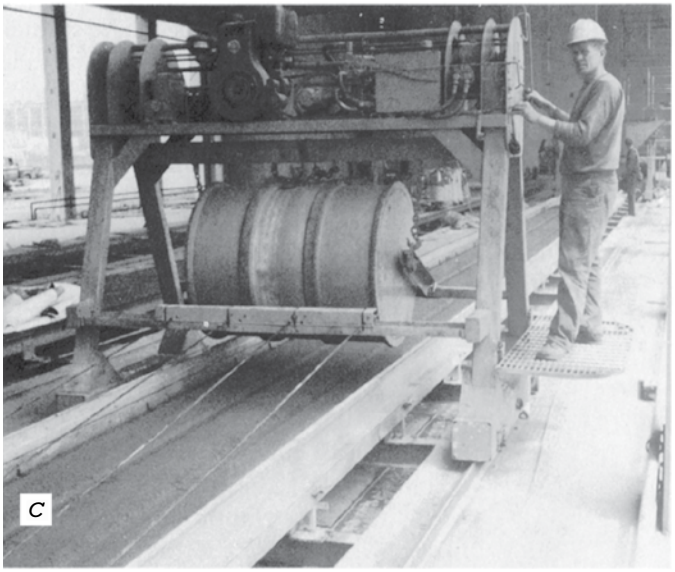
After curing, the slabs are cut to required lengths and removed from the forms. The materials used to form voids in the planks are removed, and the slabs are stockpiled to await transportation to the construction site.

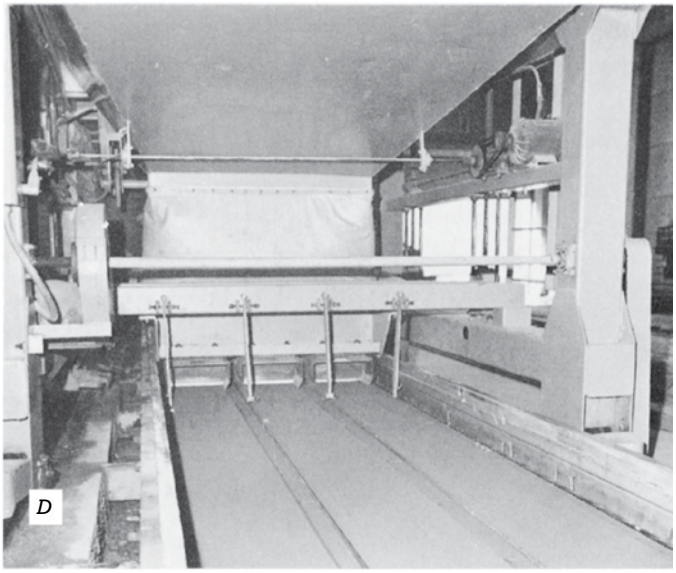
Column Production

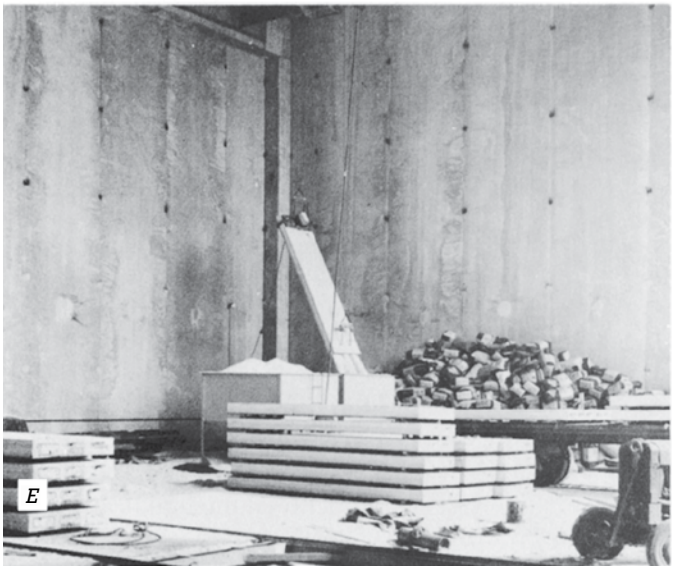
Precast concrete columns may be reinforced with ordinary mild steel or pretensioned strands. Pretensioned columns are often made and shipped in multistory lengths with *corbels* to support beams or slabs (Figures 15.16 and 15.18). Columns with corbels on one side or on two opposing sides are easily cast in flat beds. If corbels are required on three sides or on two adjacent sides, box forms are set atop the upper side of the column form as it lies in the casting bed. For corbels on the fourth side, steel plate inserts are cast into the bottom face of the column in the bed, to which reinforcing bars are welded after the column is removed from the bed. The corbels on the fourth side are then cast around the reinforcing bars in a separate operation.


A


B


C


D


E

F

FIGURE 15.11
Steps in the manufacture of a hollow-core slab. (*A*) A thin bottom slab of low-slump concrete is deposited into the casting bed with a traveling hopper. (*B*) A ridged roller compacts the bottom slab and makes indentations to key to the concrete webs. (*C*) Four prestressing strands are pulled onto the bed; these will be pretensioned with jacks. (*D*) After pretensioning, an extrusion device travels the length of the bed, forming the webs and the top of the slab and filling the cores with dry, lightweight aggregate that serves as temporary support for the fresh concrete. (*E*) The next day, after curing of the slab has been completed, a saw cuts it into the required lengths. Each length is then lifted from the bed and transported by an overhead crane to the aggregate recovery area, where the dry aggregate is poured out and saved for reuse. (*F*) Finished slabs are stockpiled, ready for transportation to the construction site. The wads of paper in the cores prevent concrete from filling the cores during pouring of the topping. *(Courtesy of Blakeslee Prestress, Inc.)*

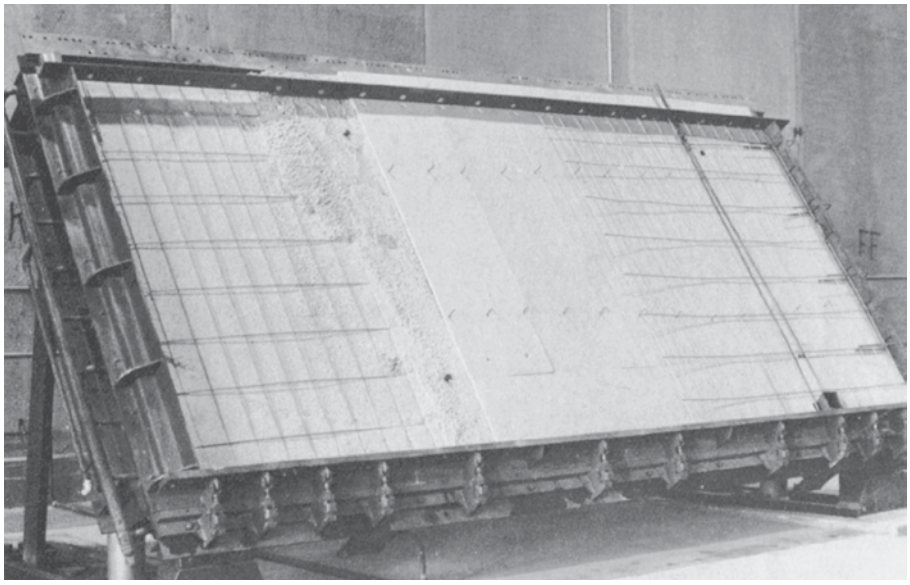


FIGURE 15.12
A tilting table being used for casting a foam-insulated concrete wall panel. To the left, a concrete panel face with welded wire fabric reinforcing is being cast. Sheets of rigid foam insulation with wire ties are seen in the center, and the welded wire fabric for the second panel face is seen at the right, with a pair of vertical bars and a pocket at the bottom being cast in as part of a system of connections. Notice the pipes at the left edge of the table for heating the mold to accelerate curing. *(Courtesy of Blakeslee Prestress, Inc.)*

Joining Precast Concrete Members

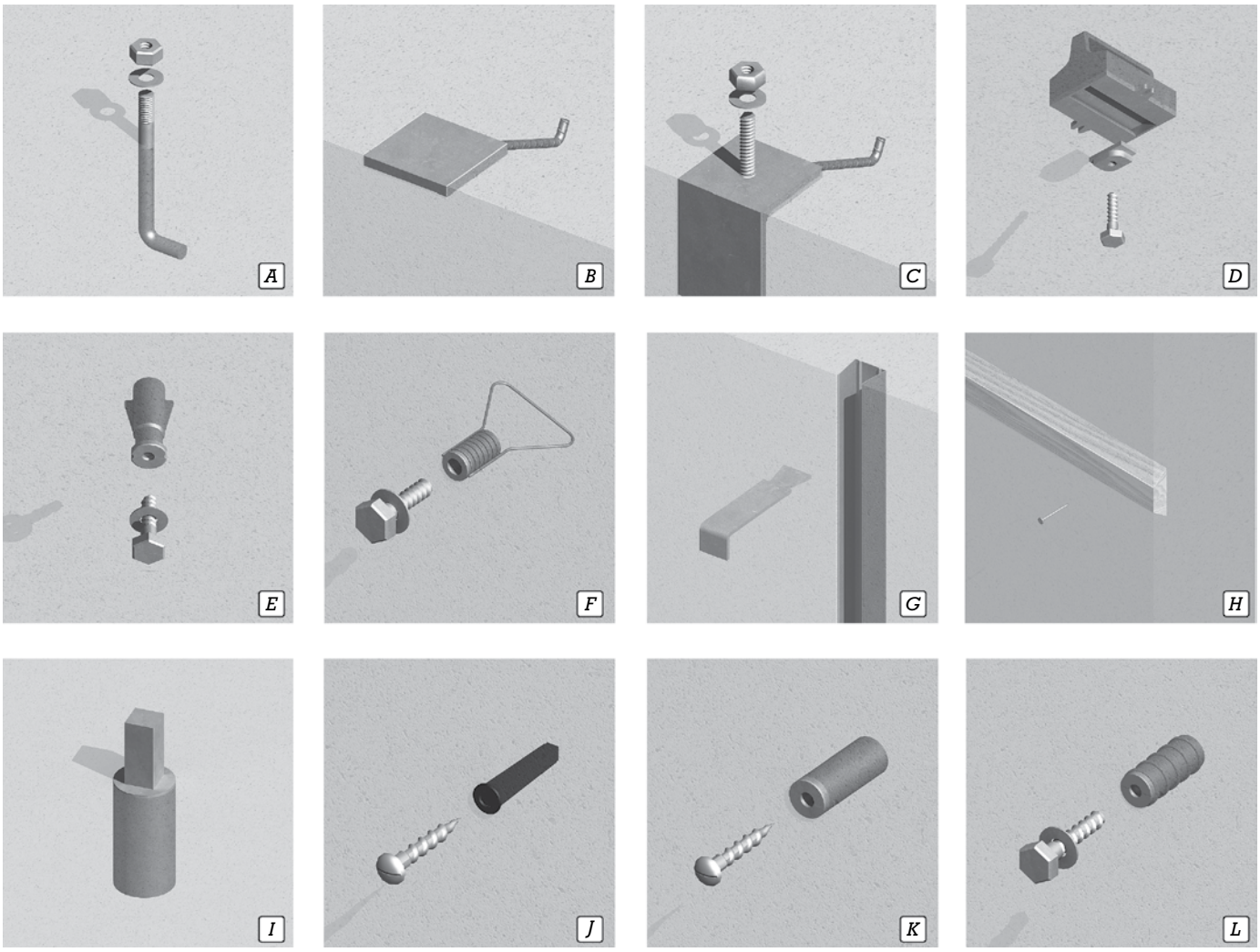
Figures 15.13 through 15.22 and 15.27 illustrate examples of frequently used connection details in precast concrete construction. Bolting, welding, and grouting are all employed. Connections can be posttensioned to produce continuous beam action at points of support (Figure 15.16). Exposed metal connectors that are not covered by topping are usually dry packed with portland cement grout (the grout is stiff but not actually dry at the time that it is installed) after being joined to protect them from fire and corrosion.

The simplest joints in precast concrete construction are those that rely on gravity by placing one element atop another, as is done where slab elements rest on a bearing wall or beam or where a beam rests on the corbel of a column. Column-to-footing or column-to-column joints are usually grouted, to create full bearing between sections (Figures 15.13, 15.14, and 15.15). Bearing walls are joined with slabs in a similar manner (Figure 15.27). With spanning members, *bearing pads* are usually inserted at points of contact. These serve to avoid the grinding, concrete-to-concrete contact that might create points of high stress (Figures 15.16 through 15.19), while also allowing for movement caused by expansion and contraction or structural deflection of the members. For solid and hollow-core slabs, these pads are strips of high-density plastic. Under elements with higher point loadings, such as tees and beams, pads of synthetic rubber are used. For resistance to seismic and wind forces, the members in these simple joints must be tied together laterally. Slab elements are often joined over supports by reinforcing bars that are cast into the topping or, where no topping is used, into the grout keys between the slabs (Figures 15.18 through 15.22). Beams, single tees, and double tees may additionally be connected by welding together steel plate inserts that have been embedded in the elements in the plant (Figures 15.18 and 15.19). The stems (lower portions) of single and double tees and the bottoms of beams are never

Fastening to Concrete

As a concrete building frame is finished, many things must be fastened to it, including exterior wall panels and facings; interior partitions; hangers for pipes, ducts, and conduits; suspended ceilings; stair railings; cabinets; and machinery. Images *A–H* show examples of fastening systems that are cast into the concrete. *A* is the familiar *anchor bolt*. *B* is a steel plate welded to a bent rod or strap anchor; this weld plate, or *embed plate*, furnishes a surface to which steel components can be welded. The steel angle in *C* has a threaded stud welded to it so that another component can be attached by bolting. *D* is an adjustable insert of malleable iron that is nailed to the formwork through the slots in the ears on either side. A special nut twists and locks into the slot to accept a bolt or threaded rod from below. Images *E* and *F* show two different designs of threaded inserts that are cast into the concrete. The sheet steel *dovetail slot* in *G* is used with special anchor straps as shown to tie masonry facings to a sitecast concrete frame or wall. The device shown in *H* is simply a dovetailed wood nailer strip cast into the concrete, suitable only for simple, very low-stress connections because the wood may absorb moisture, swell, and crack the concrete, or dry out, shrink, and become loose. Fastening systems *A–F* are heavy-duty devices that are available in capacities sufficient to anchor heavy building components and machinery.

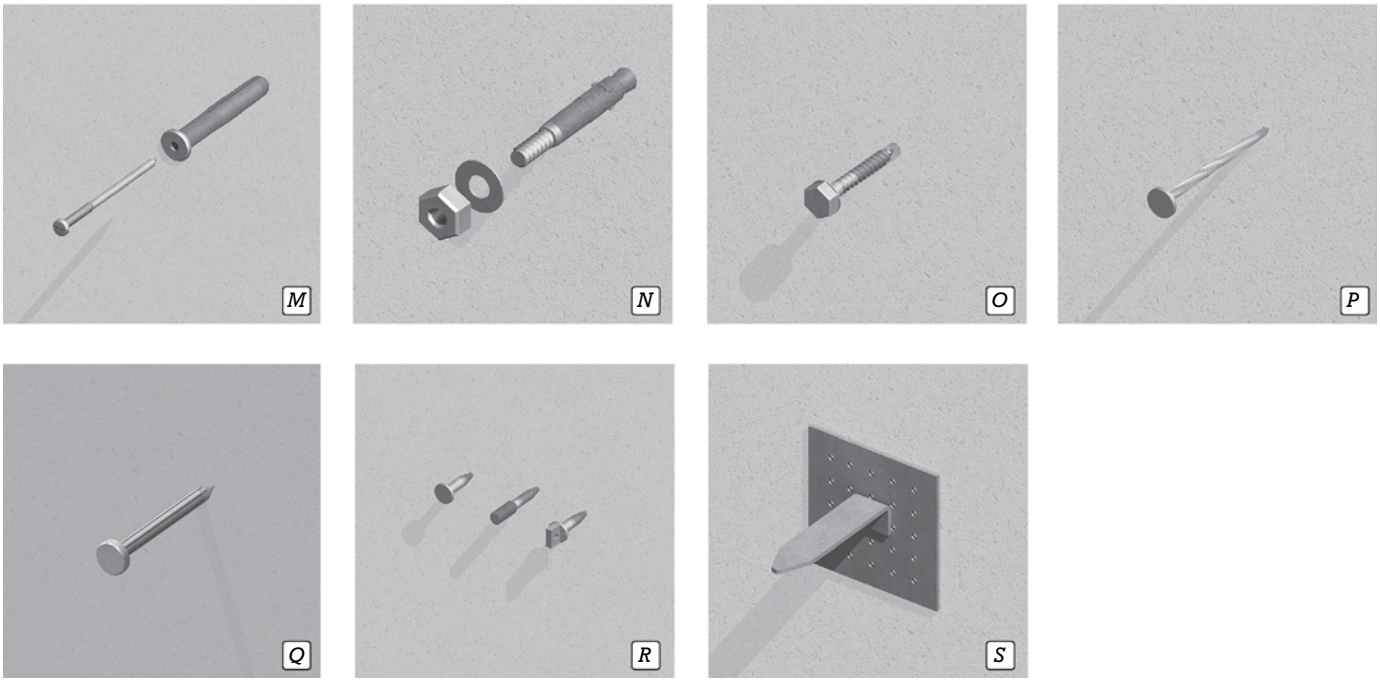
Images *I–P* depict fastening devices that are inserted in holes drilled into the cured concrete. Image *I* shows the steel post of a railing anchored into an oversized hole



in a concrete slab using grout or epoxy; this device is also used to fasten bolts to concrete and can carry heavy loads if properly designed and installed. *J* is a plastic sleeve, *K* a wood or fiber plug, and *L* a lead sleeve; all three are inserted into drilled holes and expand to grip the sides of the hole when a screw is driven into them. *M* is a similar type of metal sleeve but has a special nail that expands the sleeve as it is driven. *N* is a special bolt with a steel sleeve over a tapered shank at the inner end. The sleeve catches against the concrete as the bolt is driven into the hole and is expanded by the taper as the bolt is tightened. *O* is a special screw and *P* is a special nail, both designed to grip tightly when inserted into drilled holes of the correct diameter. Devices *J*–*P* are light- to medium-duty fasteners, with the exception of *L* and *N*, which can carry rather heavy loads.

The devices shown in *Q* and *R* are driven anchors. *Q* is the familiar concrete nail or masonry nail, made of hardened steel. If driven through a strip of wood with a few blows of a heavy hammer or inserted with a nail gun, it will penetrate concrete just enough to provide some shear resistance for furring strips and sleepers, but it has a tendency to loosen, particularly if driven with too many blows. Shown in *R* are three examples of *powder-driven* (often called *powder-actuated*) *fasteners*, which are driven into steel or concrete by an exploding cartridge of gunpowder. The first fastener is a simple pin used for attaching wood or sheet metal components to a wall or slab. The middle one is threaded to accept a nut. The eye on the fastener to the right allows a wire, such as a hanger wire for a suspended ceiling, to be attached. Powder-driven fasteners are rapidly installed, economical, and have a moderately high load-carrying capacity.

Fastener *S* typifies devices whose perforated metal plates adhere securely with a mastic-type adhesive to surfaces of concrete or masonry. The fastener shown in the image has a thin sheet metal spike, over which a panel of foam plastic insulation can be impaled. The tip of the spike is then bent across the face of the insulation panel to hold it in place.



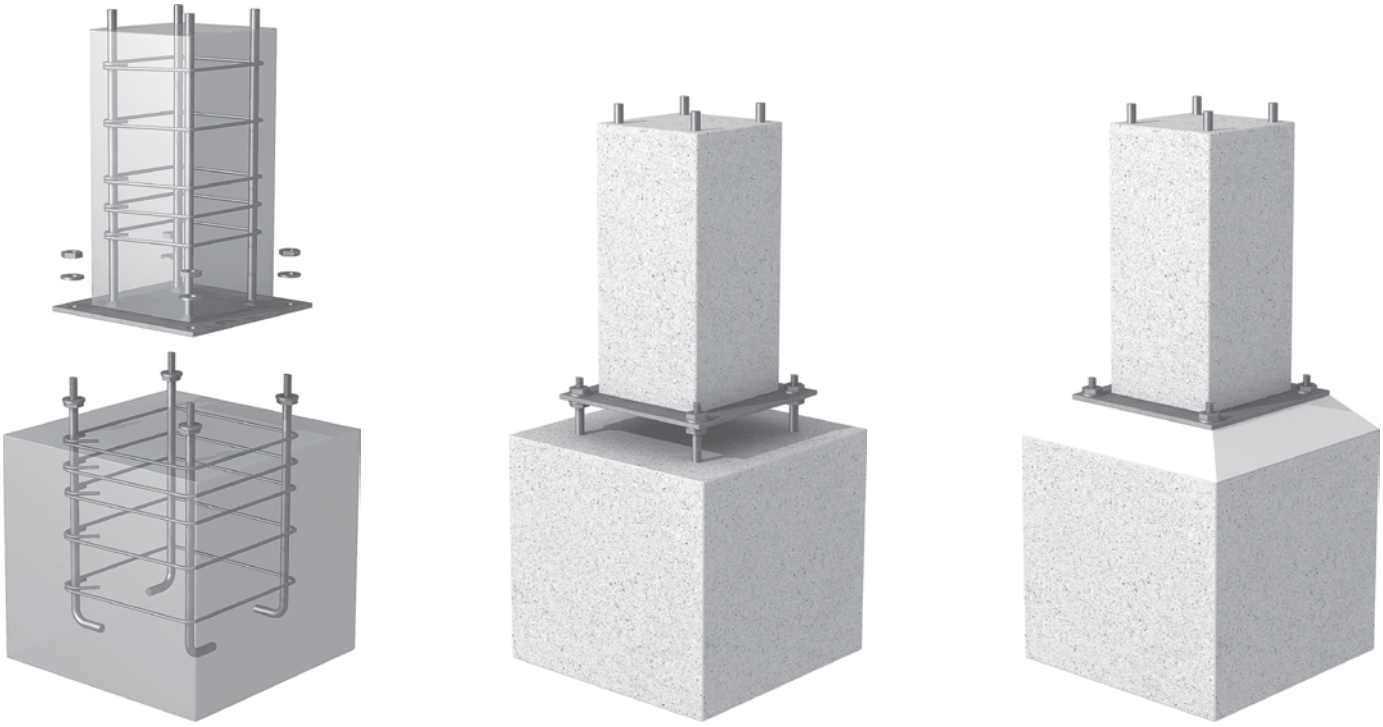


FIGURE 15.13
A simple base detail for precast concrete columns. Four anchor bolts project from the top of the sitecast foundation. Nuts and washers are placed on these bolts to support the column temporarily. The column, which was cast around steel dowels welded to a baseplate, is lowered by crane. Workers guide the column so that the anchor bolts come through the holes in the baseplate. Washers and nuts are added to the anchor bolts on top of the baseplate. The eight nuts are used to adjust the height of the column and to make it plumb. When this has been accomplished, the nuts are tightened and stiff grout is dry packed under the baseplate.

welded to the supports, but are left free to move on their bearing pads as the slab elements deflect under load.

In some cases, precast slab elements, especially solid slabs, require temporary shoring at midspan to help support the weight of the topping until it has cured. After curing, the topping becomes part of the slabs and increases their strength and stiffness. For construction economy, smooth-topped precast slab elements are sometimes used without topping. At roofs, unevenness in the precast elements is readily bridged by rigid thermal insulation placed on top. Untopped slabs may also be used for floors that will be finished with a pad and carpet and for parking garages. Or a very thin topping may be used to achieve a smooth level surface, without having any structural role. Untopped slabs require special connection details that do not rely on reinforcing bars placed in the topping (Figures 15.18 and 15.20).

Posttensioning can be used to combine precast elements into even larger ones on the site. This is done to assemble precast concrete box segments into very long, deep girders for bridges (Figures 15.23 and 15.24) and to create tall shear walls from story-high precast panels in multistory buildings. In either case, ducts for the posttensioning tendons are

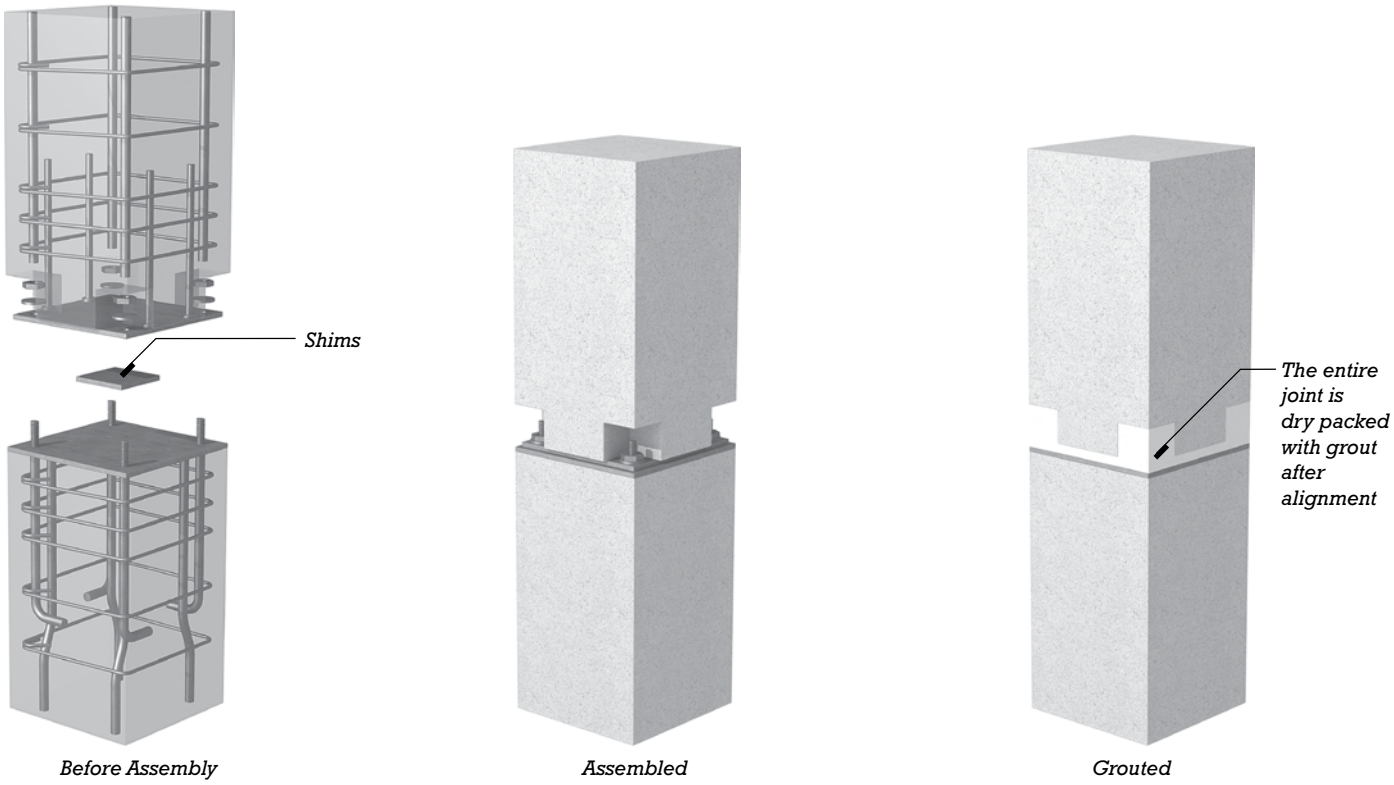
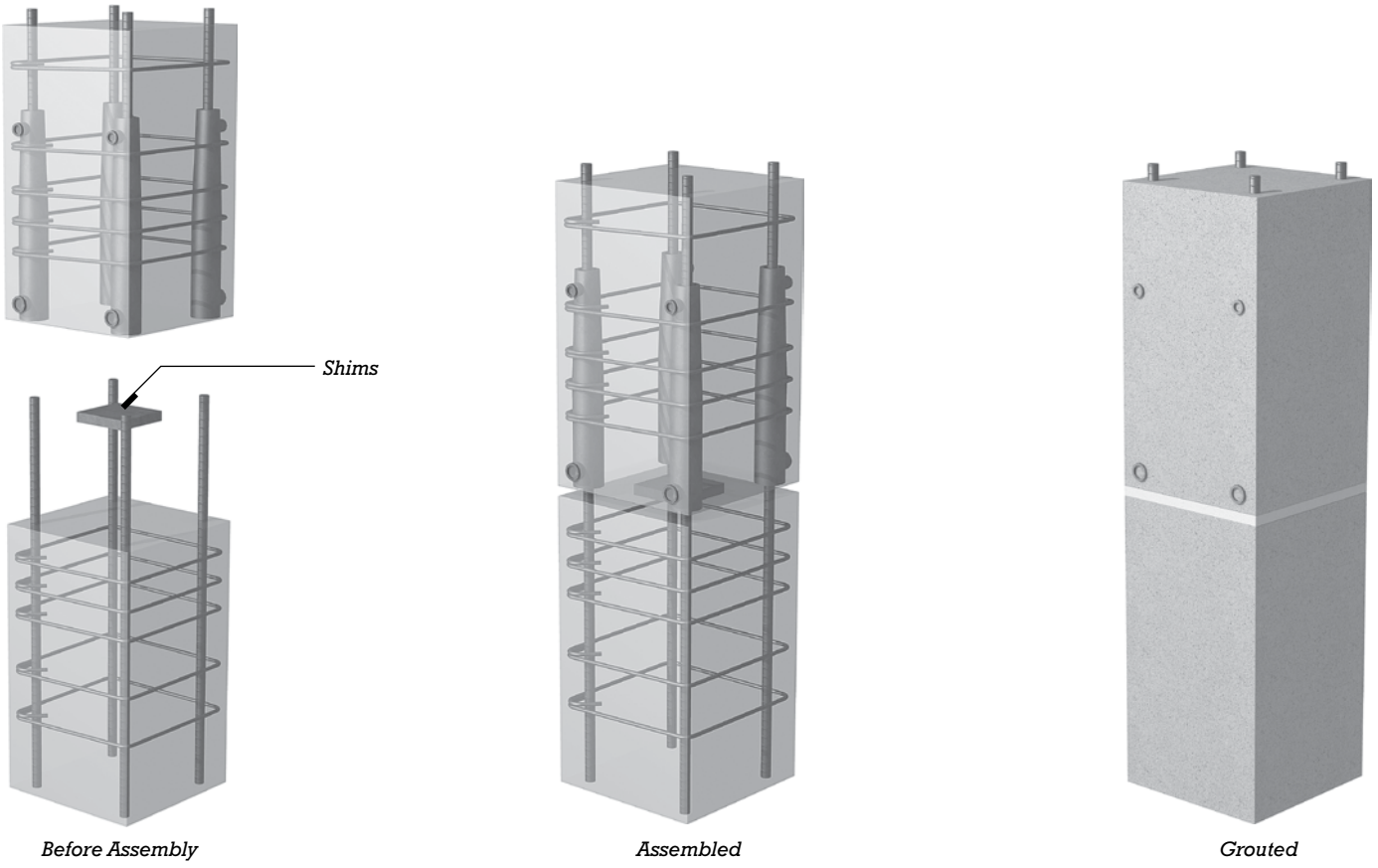


FIGURE 15.14
Similar details serve both as an alternative way of placing a column on its foundation and for column-to-column connections. Metal shims support the upper column sections at the proper height until the grout cures. The open corners are dry packed with stiff grout after the column has been aligned and bolted; this protects the metal parts of the connection from fire and corrosion.

placed accurately in the sections before casting so that they will mate perfectly end-to-end when the sections are assembled on the site. After assembly, tendons are inserted into the ducts, horizontally in the case of girders or vertically in the case of shear walls, tensioned with portable hydraulic jacks, then grouted if required.

Joint design is an area in which precast concrete technology continuous to evolve. Historically, precast concrete building construction has seen only limited application in regions of high seismic risk, due to the inability to ensure predictable, resilient performance under seismic loadings. More recently, innovations in the joining of precast concrete members have led to connection designs that can reliably absorb the energy imparted into the structure during a seismic event. Examples include unbonded posttensioning strands that allow the structure to respond elastically to seismic displacements, hybrid joint connections that combine the ductility of mild steel reinforcing with the high strength of prestressed strands, ungrouted or open-joint systems that permit controlled movements between members, and joint friction dampers that limit frame movements while absorbing seismic energy.



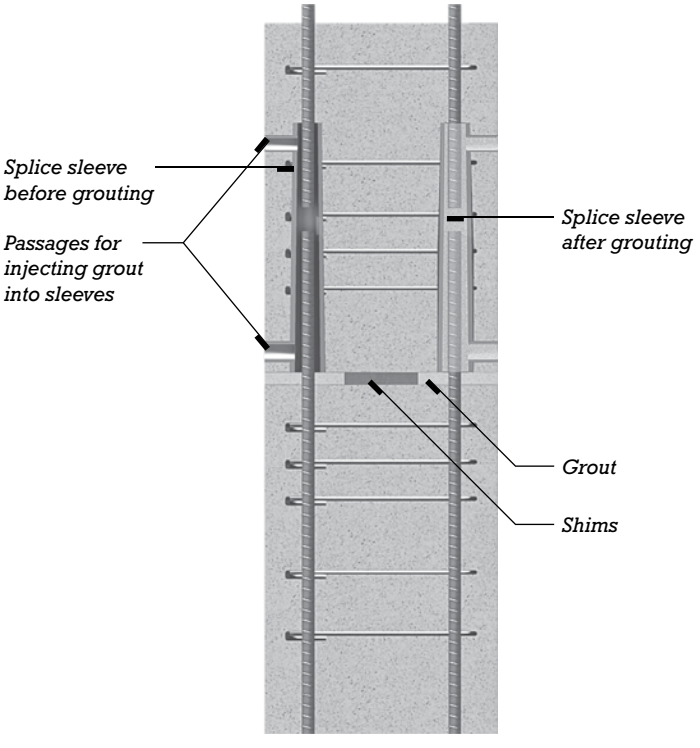


FIGURE 15.15

This column-to-column connection uses proprietary sleeves that are cast into the lower end of the upper column section. Before the sections are assembled (*upper left*), the lower ends of the vertical bars from the upper column section, which reach down to the midheight of each sleeve, are the only contents of the sleeves. Assembly of the column sections starts with the placement of a stack of steel shims in the center of the top of the lower section. These shims serve to adjust the height of the column and to maintain a space for grouting between the two sections. In the next two drawings, the sections have been assembled by lowering the upper section onto the lower one. The sleeves mate with projecting reinforcing bars from the lower column section. After the upper column section has been shimmed to exactly the right height and plumbed up, a fluid grout is injected into each sleeve, where it cures and serves to connect the reinforcing bars. A stiff grout is dry packed between the ends of the columns. The grouted sleeves develop the full strength of the reinforcing bars that they connect.

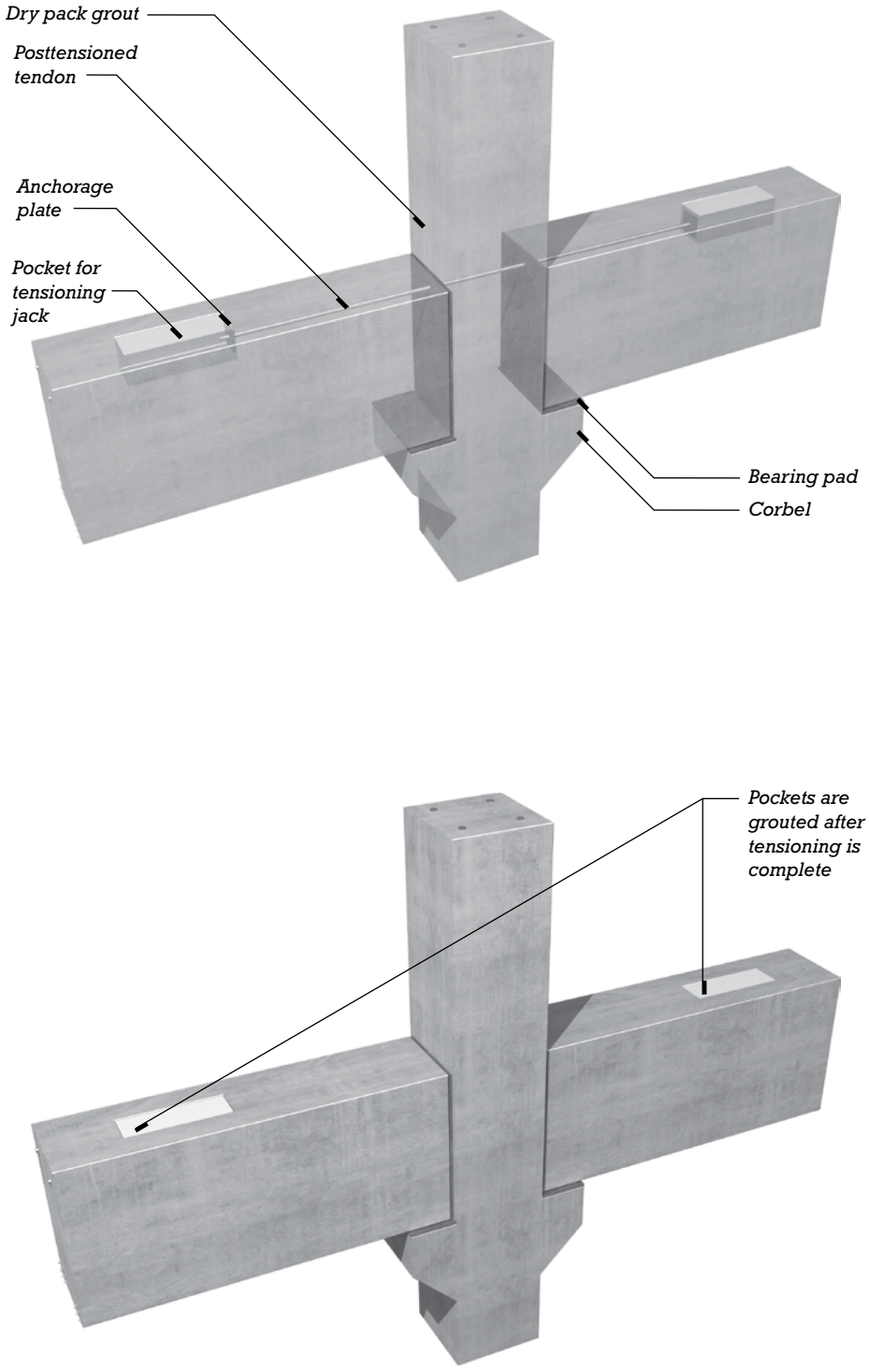


Figure 15.16
A posttensioned, structurally continuous beam–column connection may be created by passing a tendon from a pocket in the top of one beam, through the column, to a pocket in the top of the other beam. The tendon is anchored to a plate in one pocket as it is tensioned by a jack in the other pocket.

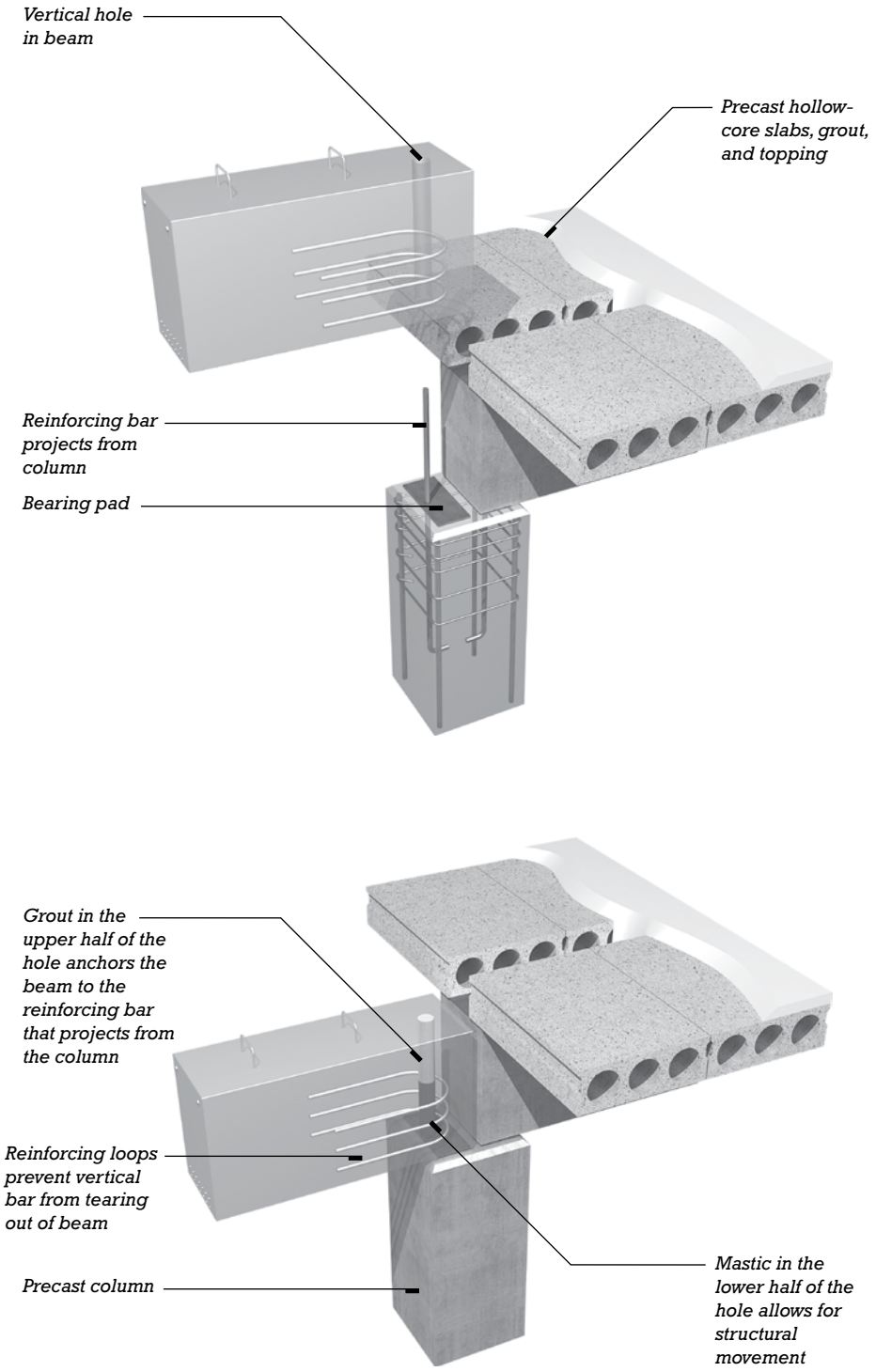


FIGURE 15.17
Topped hollow-core roof slabs supported on beams are joined to a column with vertical rods. A similar connection can be used for floor beams resting on corbels.

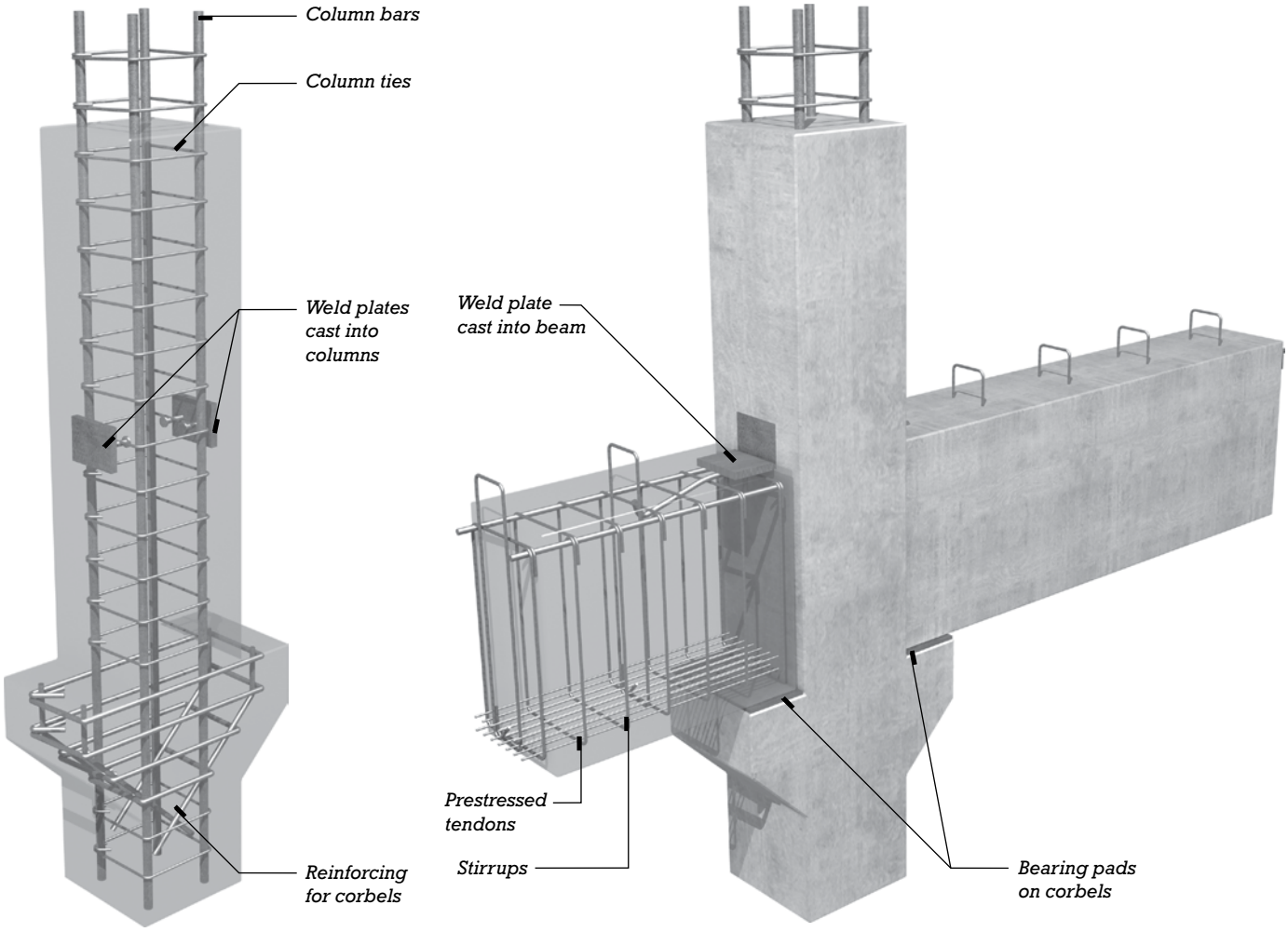
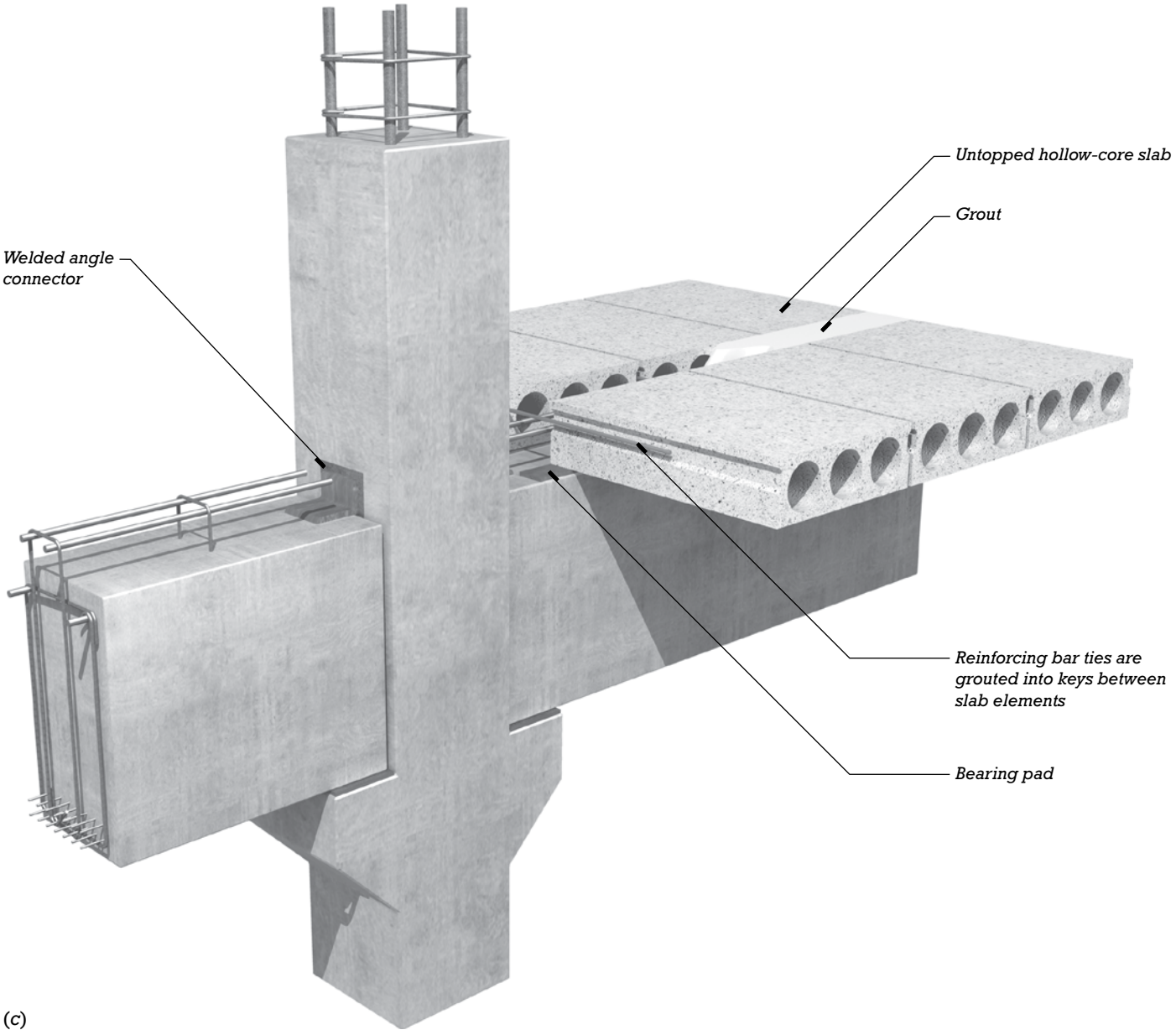


FIGURE 15.18

The beams in this system of framing rest on concrete corbels that are integrally cast with the column. The smooth-topped hollow-core slabs are detailed for use without topping. (*a*) Weld plates are cast into the column. (*b*) Beams are placed on bearing pads on the corbels. A weld plate is cast into the top of each beam at the end.

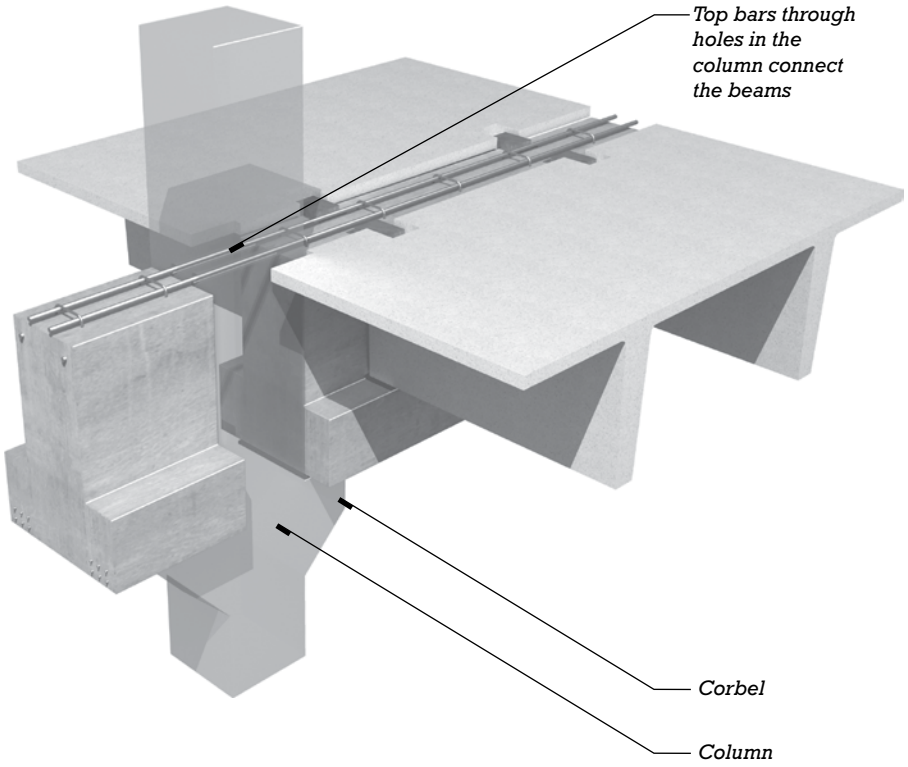
(*continued*)



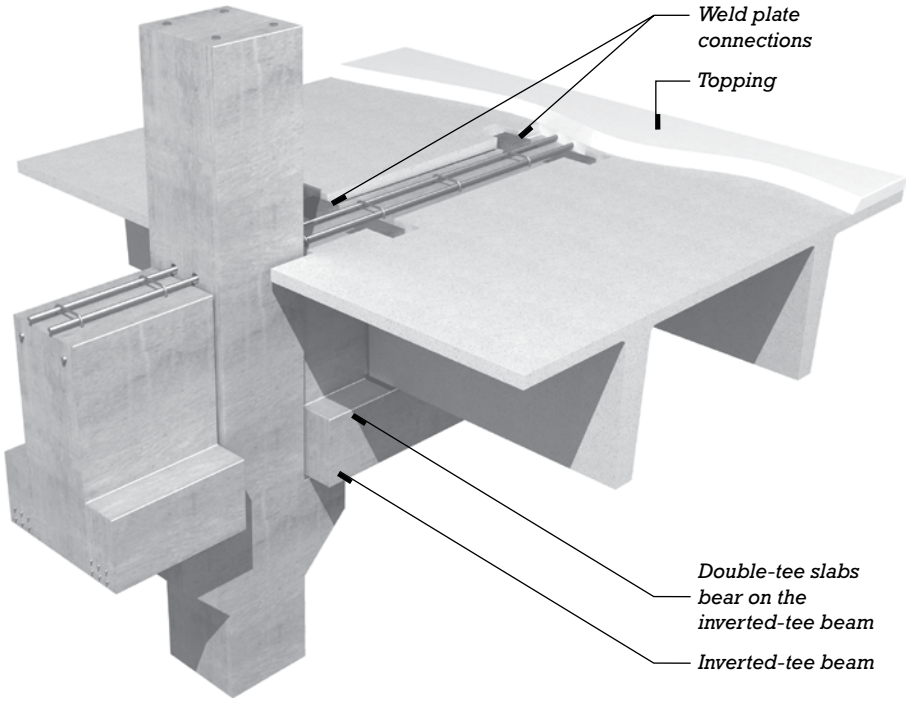
(*c*)

FIGURE 15.18 *continued*

(*c*) Short pieces of steel angle are welded to the plates to join the beams to the columns. Smooth-topped hollow-core precast concrete planks are placed on bearing pads on top of each beam. Grout is poured into the gap between the ends of the planks to unite loops of reinforcing that project from the tops of the beams, reinforcing bars that are inserted through the loops, and lateral pieces of reinforcing bar that are grouted into the keys between planks. The end result is a tightly connected assembly that supports an untopped precast concrete floor or roof.



(*a*)



(*b*)

FIGURE 15.19

(*a*,*b*) Topped double-tee floor slabs are supported by inverted-tee beams in this detail. Reinforcing bars that pass through hollow tubes cast into the column connect the beams and column.

(*continued*)

(*c*)

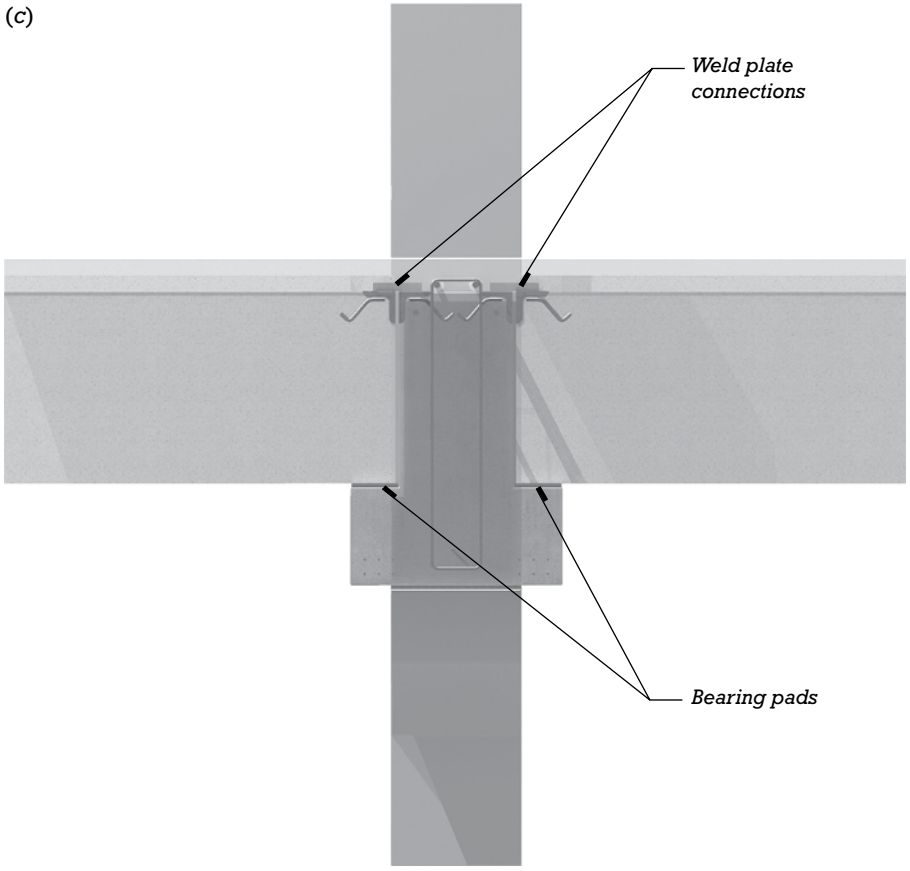
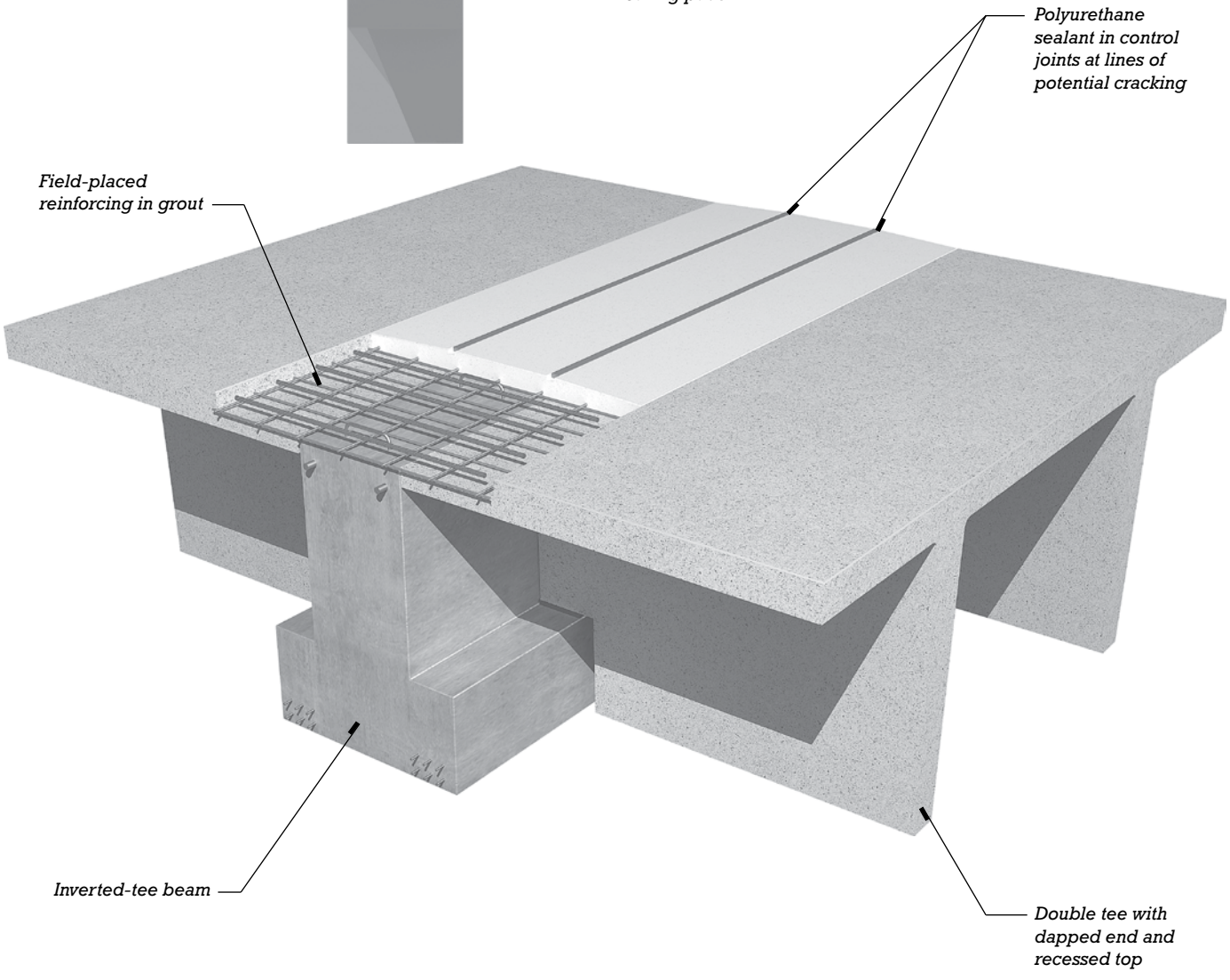


FIGURE 1519 ***continued***
(*c*) The sitecast topping ties all the components together and gives a smooth, level surface.

FIGURE 15.20
A minimum-headroom, minimum-cost floor system for parking garages uses untopped double tees. Refer to Figure 15.8 (*c*, *d*) for photographs of how the ends of the tees are detailed for use in this system. The stems of the tees are dapped so that the beam need be no deeper than the tees.



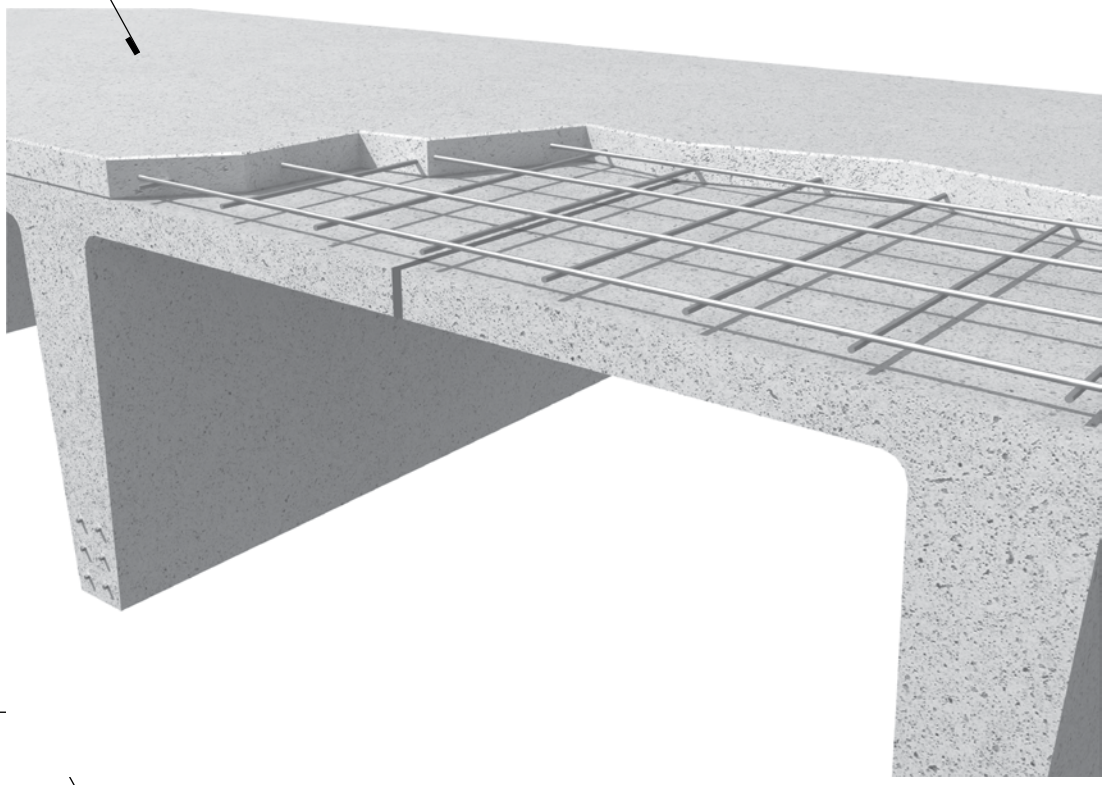


FIGURE 15.21
A cutaway view of a topped double-tee slab.

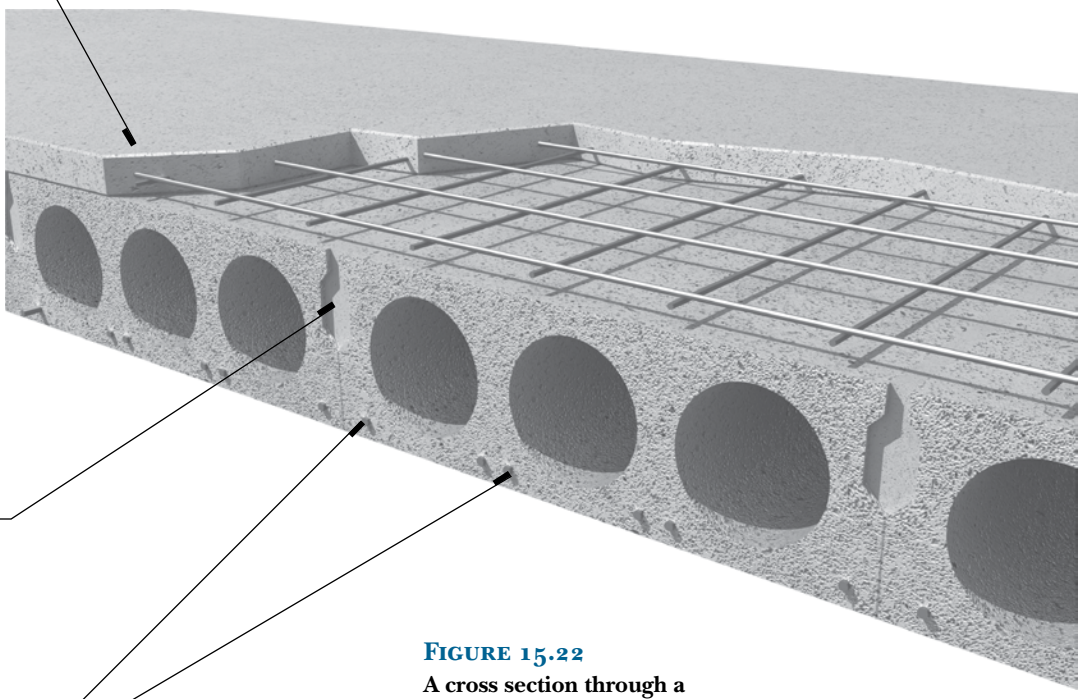


FIGURE 15.22
A cross section through a topped hollow-core slab.

FIGURE 15.23
The Linn Cove Viaduct in Linnville, North Carolina, was built of short precast segments that were posttensioned together as they were placed to form a continuous box girder deck. A section is being installed by the derrick at the extreme right. The maximum clear span is 180 feet (55 m). *(Engineer: Figg and Muller Engineers, Inc. Courtesy of Precast/Prestressed Concrete Institute.)*

FIGURE 15.24
The Linn Cove Viaduct was constructed with very little temporary shoring so as to disrupt the natural landscape below as little as possible. The precast hollow box sections formed a girder that could cantilever for long distances during construction. The box profile is highly resistant to the torsional forces that occur in a curving beam. *(Courtesy of Precast/Prestressed Concrete Institute.)*

Composite Precast/ Sitecast Concrete Construction

In *filigree precast concrete*, relatively thin precast elements that are either conventionally reinforced or prestressed are used as the formwork for sitecasting of beams and slabs. Once the process is complete, composite structural action between the sitecast concrete and precast units results in a unified, structurally efficient system. Because the precast units remain in place as part of the finished system, formwork costs are much less in comparison to conventional sitecast concrete construction methods (Figure 15.25).

The Construction Process

The construction process for precast concrete framing is much like that for steel framing. The structural drawings for the building are sent to the precasting plant, where engineers and drafters prepare shop drawings that show all the dimensions and details of the individual elements and how they are to be connected. These drawings are reviewed by the engineer and architect for conformance with their design intentions and corrected as necessary. Then the production of the precast components proceeds, beginning with construction of any special molds that are required and fabrication of reinforcing cages, then continuing through cycles of casting, curing, and stockpiling as previously described. The finished elements, marked to designate their positions in the building, are transported to the construction site as needed and placed by crane in accordance with erection drawings prepared by the precasting plant (Figures 15.26 and 15.27).

Figure 15.25
Filigree precast slab units have been set and will act as formwork for the sitecast concrete yet to be poured. Steel reinforcing has also been placed. Lightweight open-web steel joist reinforcing, cast into the precast units and partially exposed, will form the structural bond between the precast and sitecast concrete. A slab band runs from upper left to lower right in this photograph. *(Courtesy of Midstate Filigree Systems, www.filigreeinc.com.)*

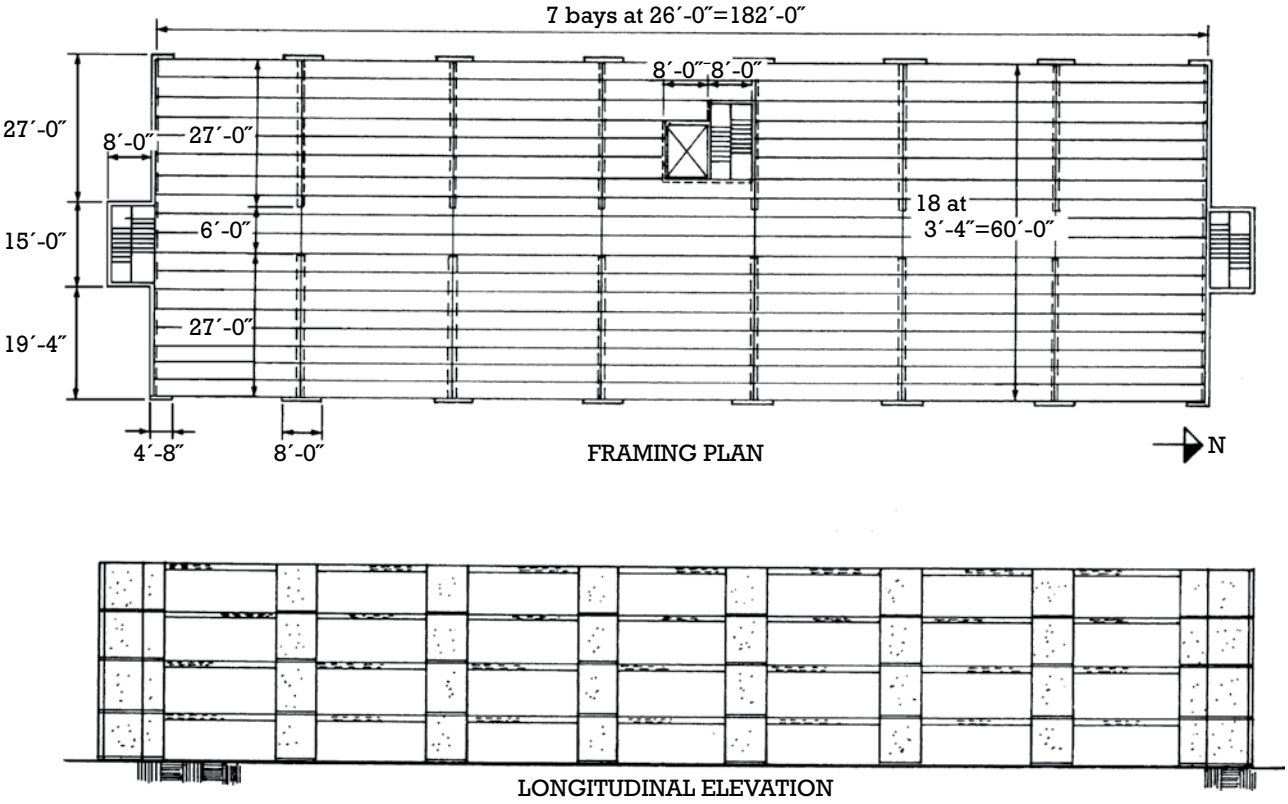


FIGURE 15.26
A framing plan and elevation of a simple four-story building made of loadbearing precast concrete wall panels and hollow-core slab elements. *(Courtesy of Precast/Prestressed Concrete Institute.)*

SUSTAINABILITY AND PRECAST CONCRETE FRAMING SYSTEMS

For considerations pertaining to the issues of sustainability of concrete construction in general, see Chapter 13.

Energy Performance

- Precast concrete wall panels with properly sealed joints have low permeability to air leakage, reducing building heating and cooling costs and contributing to good indoor air quality.

Building and Material Life-Cycle Impacts

- A North American industry average EPD reports the following average cradle-to-gate impacts per metric tonne (2200 lb) of structural precast concrete:

Nonrenewable primary energy consumption	2600 MJ (2.4 million BTU)
Global warming potential	300 kg (660 lb) CO_2 eq.
Fresh water consumption	1600 L (420 gal)

- In many cases, the optimized design of precast concrete results in elements that use less material than comparable sitecast concrete systems.
- Sometimes, precast concrete wall panels can be reused when buildings are altered.

Material and Production Attributes

- Precast concrete production encourages the reuse of formwork, reducing waste. Wood and fiberglass forms can be used up to 50 times without major maintenance. Concrete and steel forms can be reused hundreds or thousands of times.
- Because precast concrete is manufactured in a controlled, factorylike setting, raw materials are used more efficiently and less waste is produced. Gray water used in various production processes, sand used in finishing, and larger aggregate used to create voids in hollow planks can all be readily reused.

Unhealthful Materials and Emissions

- Precast concrete elements with high-quality architectural finishes reduce the need for volatile organic compound-emitting paints or other finish coatings. Concrete is not easily damaged by moisture and does not support the growth of mold.

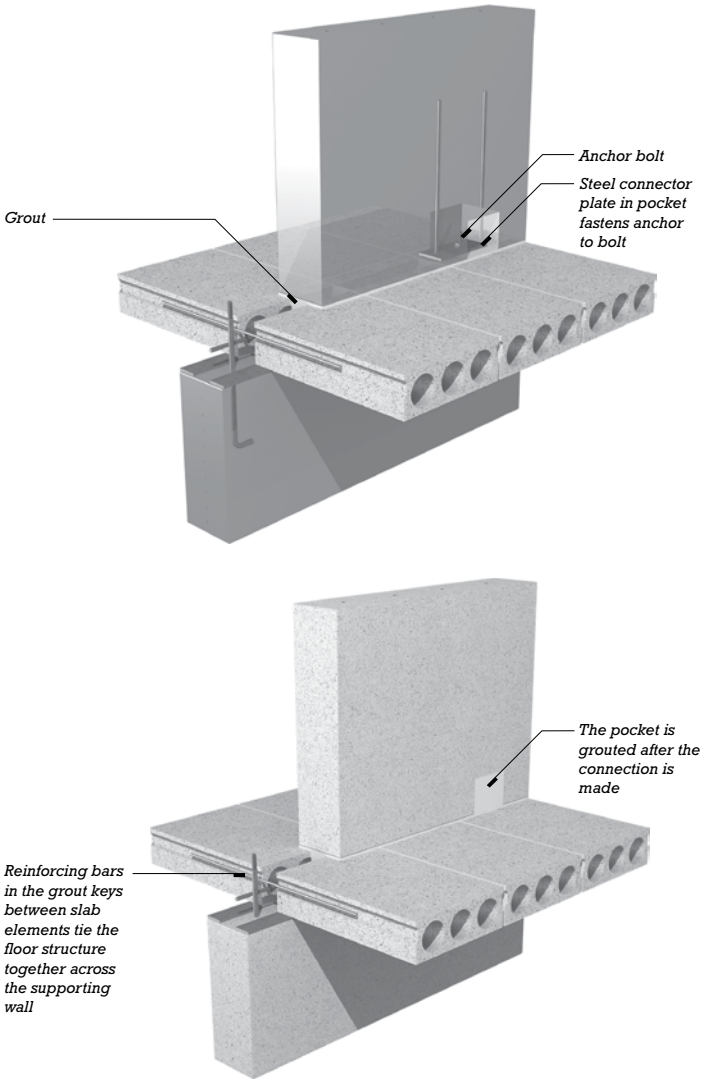


FIGURE 15.27
A typical detail for the slab–wall junctions in the structure shown in Figure 15.26. The reinforcing in the wall panels and the prestressing steel in the slabs have been omitted from these drawings for the sake of clarity.

PRECAST CONCRETE AND THE BUILDING CODES

Precast concrete is noncombustible and can be used in any building code construction, as long as it meets necessary fire resistance rating requirements (Figure 1.5). The fire resistance of precast concrete building frames and bearing wall panels depends on whether they are made of structural lightweight concrete or normal concrete, and on the amount of concrete cover that protects the prestressing strands and reinforcing bars. When the architect or engineer has determined the building construction type, the precaster can assist in determining how the necessary degrees of fire resistance can be achieved in each component. Slab elements are readily available in 1- and 2-hour fire resistance ratings, and beams and columns in ratings ranging from 1 to 4 hours. The fire resistance ratings of precast concrete slab elements may be increased by increasing the topping thickness or adding a topping where none was otherwise required. Solid and hollow-core slabs may achieve ratings as high as 3 hours by this means. Single and double tees require the addition of applied fireproofing material to achieve a fire resistance rating higher than 2 hours.

UNIQUENESS OF PRECAST CONCRETE

Precast, prestressed concrete structural elements are crisp, slender in relation to span, precise, repetitive, and finely finished. They combine the rapid all-weather erection of structural steel framing with the natural fire resistance of sitecast concrete framing to offer economical

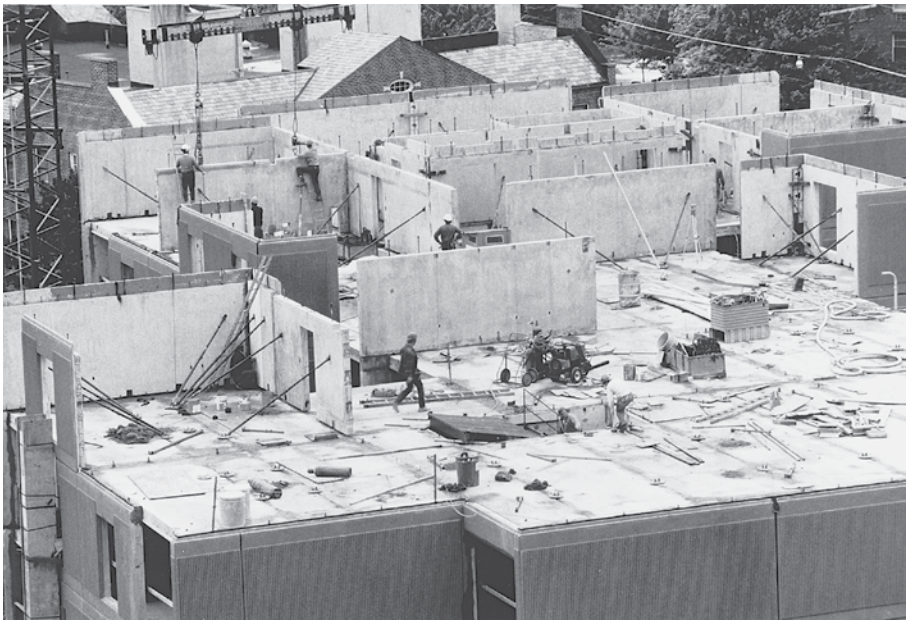


FIGURE 15.28
A view of the construction of a building that uses precast concrete loadbearing wall panels. The rectangular pockets at the lower edges of the wall panels are for bolted connections of the type shown in Figure 15.27. Steel pipe braces support the panels until all the connections have been made and the structure becomes self-stable *(Courtesy of Blakeslee Prestress, Inc.)*

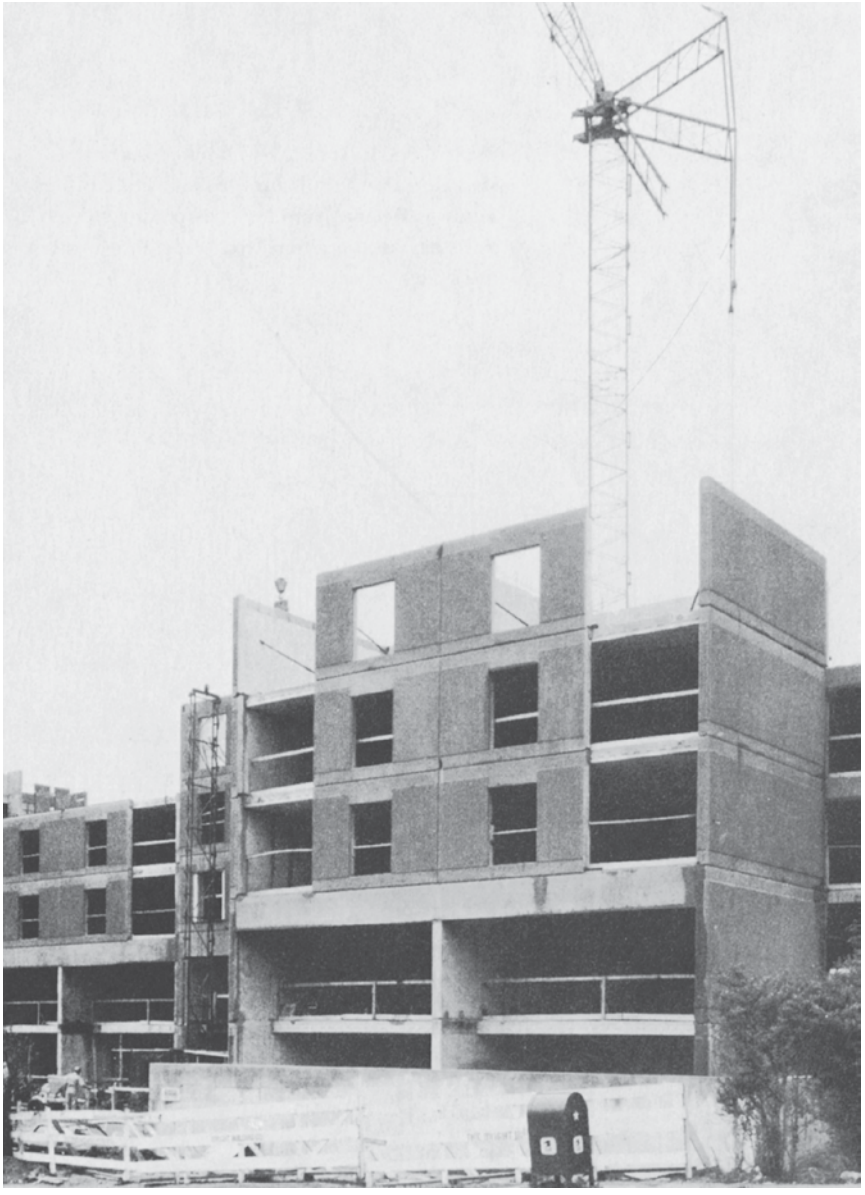


FIGURE 15.29
Exterior loadbearing wall panels are often made of specially colored concrete, with surface textures cast in. *(Courtesy of Blakeslee Prestress, Inc.)*

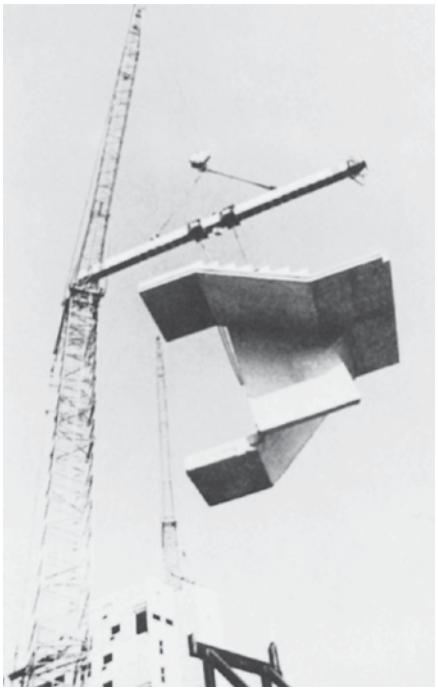


FIGURE 15.30
A crane hoists a single-piece precast stair for a high-rise building of loadbearing precast concrete wall panels. *(Courtesy of Blakeslee Prestress, Inc.)*

FIGURE 15.31
A close-up of the precast concrete building frame shown in Figure 15.32. Precast concrete columns with corbels support inverted L- and T-shaped beams. The floor structure is double tees. On the left-hand column, patches where lifting loops were burned off are can be seen. *(Photo by Joseph Iano.)*

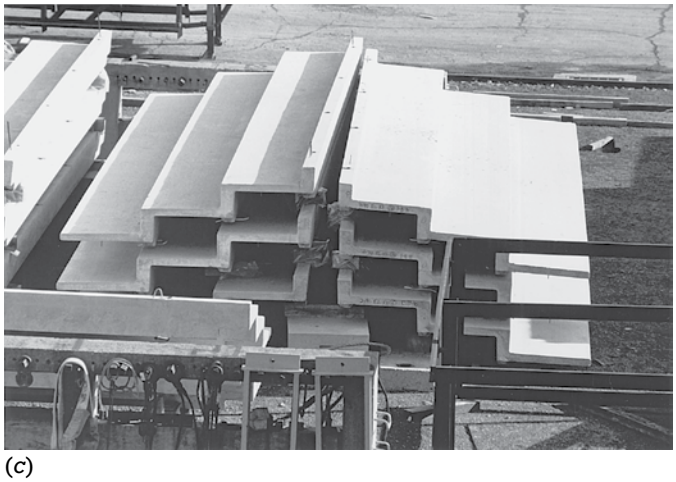
FIGURE 15.32
A precast concrete building frame with a long-span OWSJ roof structure. Details of the framing are shown in Figure 15.31. *(Photo by Joseph Iano.)*

framing for many kinds of buildings (Figures 15.28 through 15.33). Solid and hollow-core slabs have become a standard part of our structural vocabulary in schools, hotels, apartment buildings, and hospitals, where they are ideal both functionally and economically. Engineers and architects have long been comfortable with precast concrete in longer-span building types, especially parking structures, warehouses, and industrial plants, where its unique structural potential and efficient serial production of identical elements can be fully utilized and openly expressed. Though less frequently, precast concrete is also used to create public buildings of the highest architectural quality, both inside and out (Figures 15.34 through 15.36).

(*a*)

FIGURE 15.33
(*a*) A crane lifts a column section from a flatbed truck to begin erection of a tennis stadium in New Haven, Connecticut. (*b*) Grouted sleeve connectors of the type shown in Figure 15.15 were used to join the precast sections of the bents that support the grandstand seating. (*c*) Stepped sections of grandstand floor await lifting. (*d*) A precast stair section is placed. (*e*) Precast hollow-core planks will be used for miscellaneous areas of floor.

(*b*)



(*c*)

(*d*)

(*e*)

(*f*)

FIGURE 15.33 *continued*

(*f*) The relationship of the stairs, bents, and stepped floor sections is evident in this photograph of the finished stadium. (*g*) The stadium in use, after a construction process that took only 11 months. Seating capacity is 15,000. *(Structural engineer: Spiegel Zamecnik & Shah, Inc. Photos by Clark Broadbent, compliments of Blakeslee Prestress, Inc., P.O. Box 510, Branford, CT 06405; Tel: 203 481 5306.)*

(*g*)

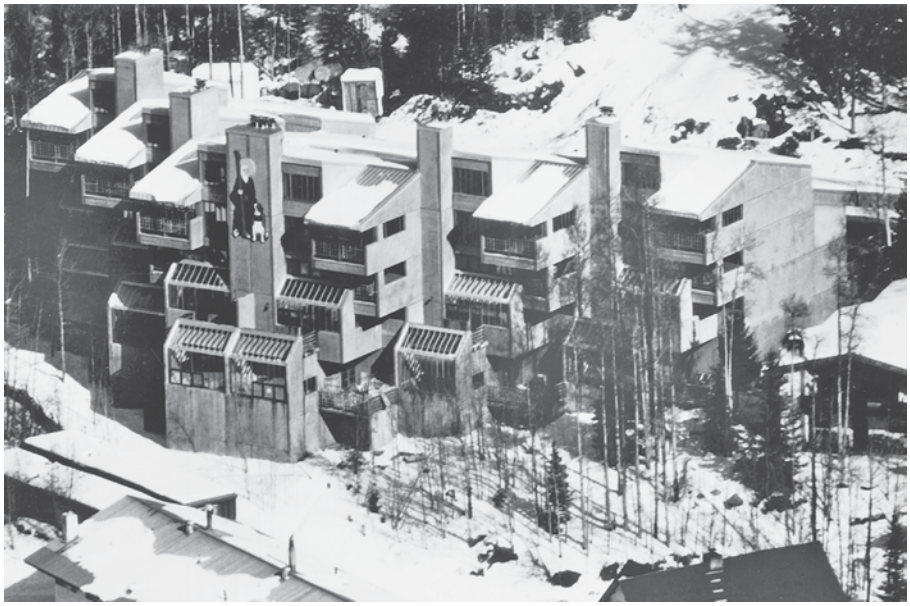


FIGURE 15.34
The precast walls and slabs of these condominium apartments were erected during the winter in the New Mexico mountains. *(Architect: Antoine Predock. Courtesy of Precast/Prestressed Concrete Institute.)*

FIGURE 15.35
Highly customized precast concrete framing is used in this courthouse by architect Eduardo Catalano. *(Photo by Gordon H. Schenk, Jr., courtesy of the architect.)*

Figure 15.36
The Stockholm Flat Iron Building, designed by Rosenbergs Arkitekter, is constructed with loadbearing precast concrete insulated sandwich panels. *(Photo by Ankara, https://commons.wikimedia.org/wiki/File:ViewfromBarnhusbron.JPG.)*

CSI/CSC MasterFormat Sections for Precast Concrete Framing Systems

03 41 00	**PRECAST STRUCTURAL CONCRETE**
03 41 13	Precast Concrete Hollow-Core Planks
03 41 16	Precast Concrete Slabs
03 41 23	Precast Concrete Stairs
03 41 33	Precast Structural Pretensioned Concrete
03 41 36	Precast Structural Posttensioned Concrete
03 45 00	**PRECAST ARCHITECTURAL CONCRETE**
03 53 00	**CONCRETE TOPPING**

Key Terms

precast concrete
steam curing
solid slab
hollow-core slab, hollow plank
double tee
single tee
topping
ledger
L-shaped beam
inverted tee
architectural precast concrete
casting bed
weld plate
dapped end
carbon fiber reinforcing
extruded process
wet-cast process
slip-form process
corbel
anchor bolt
embed plate
dovetail slot
powder-driven fastener, powder-actuated fastener
bearing pad
filigree precast concrete

Review Questions

1. Under what circumstances might a designer choose a precast concrete framing system over a sitecast system? Under what circumstances might a sitecast system be favored?
2. Why are precast concrete structural elements usually cured with steam?
3. Explain several methods of producing hollow-core slabs.
4. Diagram from memory several different ways of connecting precast concrete beams to columns.
5. Diagram from memory a method of connecting a pair of untopped double-tee slabs to an inverted-tee beam. Then work out a similar way of connecting a double tee to an L-shaped beam, as would occur around the perimeter of the same building.
6. Explain the construction process for a filigree precast concrete system. What are the unique advantages of this system over other concrete systems?

Exercises

1. Design a simple two-story rectangular warehouse, 90 × 180 feet (27 × 54 m), using precast concrete for the floor and roof structure and for the walls as well. Use the preliminary structural design information given in this chapter to help determine the column spacing, the types of elements to use, and the depths of the elements. Draw a framing plan and typical connections for the building.
2. Locate a concrete precasting plant in your area and arrange a visit to view the production process. If possible, arrive at the plant early in the morning, when the strands are being cut and the elements are being lifted from the molds.
3. Learn from the management of the precasting plant where a precast concrete building is being erected, then visit the building site. Trace a typical precast concrete structural element from raw materials through precasting, transporting, and erecting. Are there ways in which this process could be made more efficient? Sketch a few of the typical connections being used in the project.

Selected References

Precast/Prestressed Concrete Institute. *Architectural Precast Concrete* (3rd ed.). Chicago, 2007.

This design manual provides technical and design guidelines for achieving high-quality architectural finishes in precast concrete, and includes hundreds of images and line drawings.

Precast/Prestressed Concrete Institute. *Design and Typical Details of Connections for Precast and Prestressed Concrete* (2nd ed.). Chicago, 1988.

Though dated, this design manual is still an industry standard and includes a large collection of drawings of standard connection details.

Precast/Prestressed Concrete Institute. *Erector's Manual: Standards and Guidelines for the Erection of Precast Concrete Products.* Chicago, 1999.

The 96 pages of this manual describe and illustrate the best ways of hoisting and assembling the elements of a precast concrete building.

Precast/Prestressed Concrete Institute. *PCI Design Handbook.* Chicago, updated regularly.

This is the major reference handbook for those engaged in designing precast, prestressed concrete buildings. It includes basic building assembly concepts, load tables for standard precast elements, engineering design methods, and a few suggested connection details.

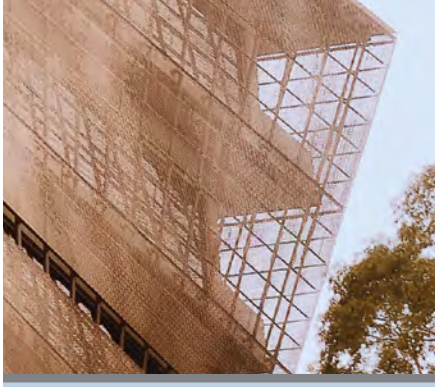
Websites

Altus Group (carbon reinforced precast concrete): altusprecast.com

National Precast Concrete Association: precast.org

Precast/Prestressed Concrete Institute (PCI): www.pci.org

Spancrete: www.spancrete.com



16

Designing the Building Enclosure

- **Functional Requirements of the Building Enclosure**
  - Keeping Water Out
  - Controlling the Flow of Heat
  - Controlling Air Leakage
  - Controlling the Diffusion of Water Vapor
  - Secondary Functions of the Building Enclosure

Sustainability and the Building Enclosure

- **Keeping Water Out**
  - Keeping Water Away
  - Eliminating Openings
  - Neutralizing the Forces That Move Water
- **Controlling the Flow of Heat**
  - Thermal Insulation
  - Insulated Enclosure Assemblies
  - Thermal Bridging
  - Radiant Heat Barriers
- **Controlling Air Leakage**
  - Air Barriers
  - Air Barrier Assemblies and Systems
  - Air Barrier Location
  - Air Barriers and Moisture Control
- **Controlling the Diffusion of Water Vapor**
  - Water Vapor Diffusion in Building Assemblies
  - Vapor Retarders
  - Vapor Retarder Usage
  - Exterior Insulation and Controlling Condensation
- **Sealing Joints in the Exterior Wall**
  - Joint Seal Materials
  - Installing and Sizing Sealant Joints
  - Interior Sealant Joints and Indoor Air Quality

The de Young Museum, San Francisco, by architect Herzog & de Meuron. The building's outer skin consists of perforated copper panels allowed to patina naturally. *(Photo by Joseph Iano.)*

The *building enclosure* (also called the *building envelope*) separates the indoor environment from the outdoors so that building occupants remain comfortable, interior conditions are suitable for the building's uses, and the components of the building structure and finishes themselves are protected. Roofs, exterior walls, basement walls, slabs on grade, doors, windows, and skylights are all example parts of the building enclosure.

Design of the building enclosure is an intricate process that merges art, science, and craft in the satisfaction of the many demands placed on these parts of the building. Some elements of the building enclosure are also visually prominent and play important roles in the building's architectural expression. A part of the building with uniquely complex functional requirements and exposed to the harshest conditions is at times, also, among the most important to our visual and spatial appreciation of the building.

In this chapter, the physical principles underlying the design of the building enclosure are presented. In following chapters, the application of these principles is illustrated in the many types of wall, roof, and fenestration systems discussed.

FIGURE 16.1
Building enclosure elements—exterior walls, windows, and roofs—create the visual fabric of a downtown urban center. *(Photo by Joseph Iano.)*

FUNCTIONAL REQUIREMENTS OF THE BUILDING ENCLOSURE

Keeping Water Out

One of the building enclosure's most important functions is to prevent unwanted entry of rain, snow, ice, and groundwater. Excess water within building assemblies can damage finish materials and the structure, promote the growth of mold and mildew, and cause unhealthful conditions for building occupants.

On roofs, snow or water can accumulate, making even small imperfections in the roofing system vulnerable to water entry. On exterior walls, preventing water entry is complicated by the wind, which can force water through small openings and in any direction, even upward. Below grade, the building substructure must resist the constant presence of moisture in the ground and sometimes forceful hydrostatic pressures when it extends below the water table.

Even with the best design and construction practices, it is unrealistic to expect the building enclosure to forever remain completely free from water ingress. For this reason, the enclosure must also be able to tolerate the presence of reasonable quantities of moisture. And it should include provisions for allowing unwanted moisture to escape and assemblies to dry. These may include drainage pathways to the exterior, ventilated cavities through which moisture can evaporate, and permeable materials within the enclosure assembly through which water vapor can diffuse.

Controlling the Flow of Heat

At the time of this writing, approximately 25 percent or more of the energy used in an average North

American commercial building can be attributed to counteracting heat losses and gains through the building enclosure.

When heat flows directly through solid materials, it is called *thermal conduction*. Unwanted heat flows through enclosure assemblies are minimized by including materials resistant to conduction, called insulation. A well-insulated building enclosure is an essential part of the design strategy for any high-performance, low energy-use building.

A thermally efficient building enclosure is also important to maintaining occupant comfort. It minimizes uneven interior air temperatures. And it prevents uncomfortable thermal radiant environments. When the interior sides of exterior walls or ceilings underneath roofs become too warm or too cold, radiant heat exchange with these surfaces can cause occupants to feel uncomfortably warm or chilled even when the ambient air temperature remains within an acceptable range.

Controlling Air Leakage

When air passes through the building enclosure, it also transports heat, a form of energy transfer called *thermal convection*. Some estimates of building energy loss from air leakage range as high as 30 to 40 percent of the total losses through the enclosure. Like the control of thermal conduction, minimizing heat loss from air escaping through the enclosure, or leaking in from the exterior, is essential to high-performance building design.

When warm air passes through the building enclosure, it also carries with it water vapor. If that moisture-laden air encounters colder temperatures, condensation and moisture damage can occur. In fact, in contemporary buildings, preventing moisture damage from air leakage is second in importance only to keeping exterior water out when considering the long-term durability of the building enclosure.

Air leakage from outside the enclosure to inside can also impact occupant well-being. Outside air infiltration introduces unfiltered air pollutants and unconditioned air into the building's interior, where it degrades indoor air quality and reduces occupant comfort.

Controlling the Diffusion of Water Vapor

Water vapor—always present in the air in an invisible, gaseous state—can also pass through the building enclosure when it diffuses directly through solid materials in an assembly. In cold climates, humid, heated interior air has a higher vapor pressure than the drier, colder outside air. Under these conditions, there is a steady movement of gaseous water molecules from the inside of the building, through the enclosure materials, to the outside. If the rate of diffusion is too high, condensation, moisture damage, and the growth of mold and mildew can occur. Conversely, in hot, humid climates, water vapor can diffuse from the outside of the building inward toward the cooler, drier, interior, and if not properly managed, also have harmful effects.

Secondary Functions of the Building Enclosure

Controlling Solar Radiation and Daylight

Windows, curtain walls, skylights, and other transparent openings in the building enclosure provide views to the outside for building occupants. These openings admit daylight, which if managed well can reduce reliance on energy-consuming electric lighting and create a more healthful, productive interior environment. Such openings must also be designed to prevent excessive interior solar heat gains, prevent glare, minimize unwanted heat losses, limit the destructive effects of the sun's rays on light-sensitive materials, and prevent excessively low temperatures on the interior side of the glazing that can cause condensation or occupant discomfort. The thermal and radiant properties of glazing materials are discussed in greater detail in Chapter 18.

Resisting Wind Forces

The exposed exterior faces of the building enclosure must withstand positive pressure and suction forces created by the wind acting across those surfaces. For low buildings or those in sheltered locations, these forces are relatively small and easily accounted for within normal construction practice.

However, the enclosures of taller or more exposed buildings must be deliberately designed to resist higher wind forces. For example, with buildings in coastal hurricane zones, the attachment of shingles or other roofing materials must be secure enough to prevent these coverings from being torn away by the high-speed winds to which they will be exposed. For tall buildings, wind forces acting on the enclosure generally increase with the height above ground, but also vary across the face of the enclosure. Frequently, the highest forces are negative (suction) pressures acting close to the corners and edges of the enclosure face, where the wind accelerates as it moves past these areas (Figure 16.2).

Adjusting to Movement

Many forces are always at work throughout a building, tugging and pushing on the building frame and its enclosure. The enclosure experiences thermal expansion and contraction as it is subjected to daily and seasonal temperature changes. Its outermost cladding layer frequently undergoes larger and more rapid daily changes compared to the layers behind because of its direct exposure to daytime solar radiation and the cold nighttime sky. Many cladding materials expand and contract with changes in moisture content. Bricks, which leave the kiln very dry, undergo

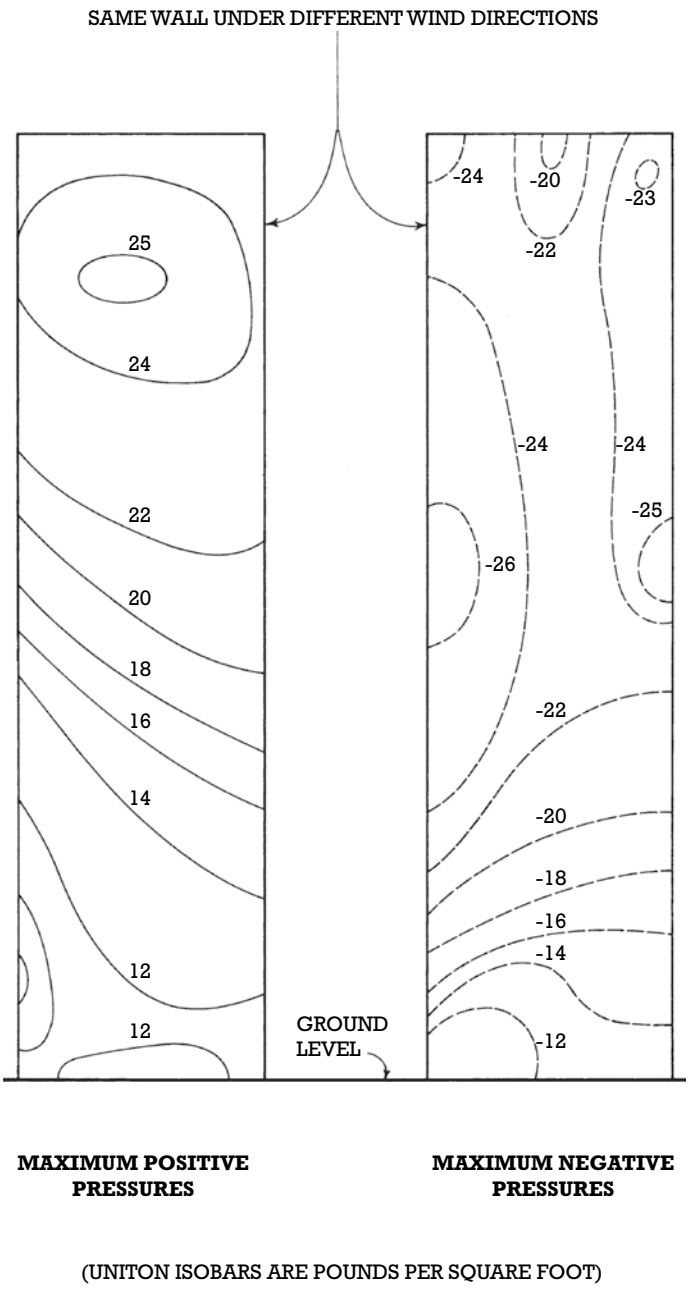


FIGURE 16.2

A diagram of positive and negative wind pressures acting on the face of a building, shown here in elevation. The building modeled in this case is 64 stories tall and triangular in plan. Notice how pressures vary greatly across the building surface, and that negative (suction) pressures are at least as high as the positive pressures. The wind's interaction with a building structure depends on the direction and speed of the wind, the height, shape, articulation, and orientation of the building, local topography, and the effects of surrounding structures. For the design of tall buildings, such effects are studied in computer models and with scale physical models tested in wind tunnels. ***(Reprinted the* Aluminum Curtain Wall Design Guide, *with permission from the AAMA.)***

a slow but prolonged expansion as they gradually reabsorb moisture from the atmosphere. Many building stones also continue to expand slightly after they are installed. Concrete materials shrink after installation as chemical hydration continues within the material. Wood routinely expands and contracts with changes in moisture content (Figure 16.3).

Meanwhile, the building frame undergoes its own movements. It may be distorted by uneven settling of the foundation. Gravity causes beams and girders to sag. The lateral forces of wind and earthquake cause sideways sway and wracking. Concrete columns shorten due to long-term creep. Posttensioning of concrete causes contraction in floor plates.

For all these reasons, the enclosure system itself, and its connections and interfaces with the building frame, must be designed to tolerate the movements that can occur without compromising the structural capacity, functionality, or visual quality of these systems (Figure 16.4).

Resisting Fire

Building enclosure resistance to fire is regulated by the building codes. Building height and area, along with the activities taking place within the building, determine a building's construction type. This, in turn, determines whether parts of the building, including the enclosure components, can be constructed of combustible

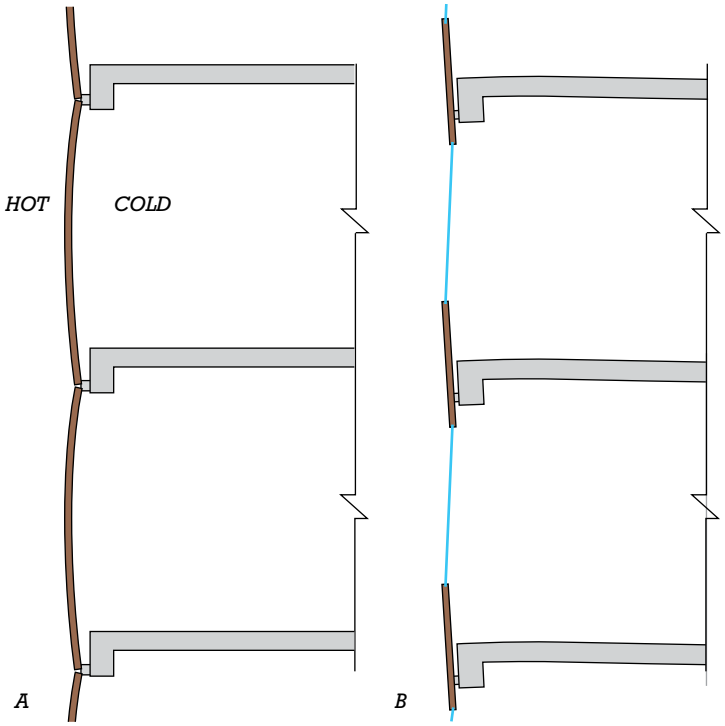


FIGURE 16.3
Distortions of curtain wall panels, illustrated in cross section. (*A*) Bowing, caused in this case by greater thermal expansion of the outside skin of the panels than of the inside skin under hot summertime conditions. (*B*) Twisting of spandrel beams because of the weight of the curtain wall.

materials (such as wood) or only those that are noncombustible (such as metals, concrete, and masonry).

When one building is constructed close to a property line or to another building on the same parcel, codes establish minimum fire resistance ratings for the building's exterior walls to reduce the risk of a fire in one building easily spreading to the other. Windows and other openings in such exterior walls, and even roof coverings, must meet similar requirements.

For buildings taller than approximately 40 to 60 ft (12 to 18 m), materials within the exterior wall must meet special requirements relating to combustibility and resistance to flame spread, which are intended to prevent the spread of fire on building exteriors at heights beyond the reach of ground-based firefighting equipment.

In areas of high wildfire risk, codes regulate combustibility, fire resistance, and flame spread for exterior walls, roofs, windows, and other parts of the building enclosure, to reduce the risk of fire in the surrounding landscape spreading to the building itself.

Controlling the Passage of Sound

The building enclosure can exclude outside noise from the interior. Especially for sensitive occupancies—for example, hospitals, schools, and performance halls—or in noisy environments—such as buildings close to a major airport—the enclosure's ability to isolate occupants from outside noise may be an important criterion.

Where transmission of sound through the enclosure is a concern, windows, solid walls, and other parts of the enclosure can be designed to meet specified sound transmission criteria. The *Outdoor-Indoor Transmission Class* (*OITC*) rating of an enclosure assembly is a measure of its resistance to the transmission of sound, with particular weight given to the lower frequencies commonly associated with street noise, airport activity, and so on. The higher the class rating, the less sound is transmitted through the enclosure. Sound Transmission Class (STC) ratings, formulated for measuring sound transmission through interior assemblies, may be applied to the design of exterior assemblies as well. See Chapter 22 for more information about STC ratings.

Durability and Resilience

Materials in the building enclosure must be resistant to the effects of exterior exposure to water, temperature extremes, and sunlight. Metals must be corrosion-resistant or provided with protective coatings, woods must be naturally resistant to decay or suitably treated, tile and masonry must be resistant to freeze-thaw, and plastics must not degrade under prolonged exposure to the sun.

Where the building enclosure is important to the visual qualities of the exterior, materials should be used that age and weather gracefully, and that will remain attractive over the life of the building. Design of the building enclosure should also account for maintenance and exterior access needs for repair of exterior materials, glass replacement, and other remedial activities.

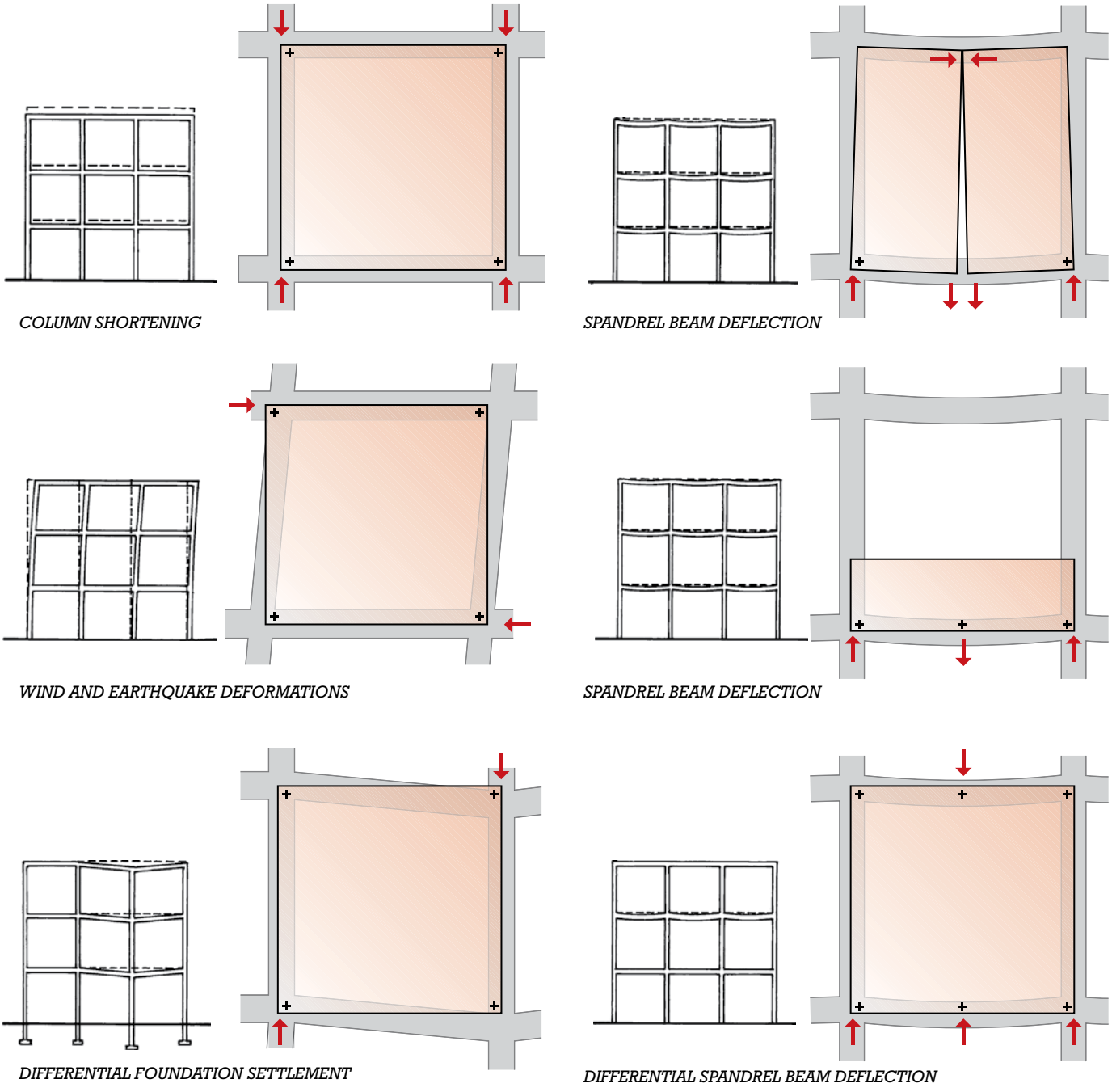


Figure 16.4

Forces on curtain wall panels caused by movements in the frame of the building, illustrated in elevation. In each of the six examples, the diagram to the left shows the movement in the frame of the building, and the larger-scale drawing to the right shows the impact of this movement on the cladding panels (shaded in gray) covering one bay of the building. Points of attachment between the panels and the frame are shown as crosses. The black arrows indicate forces on the wall panels caused by the movement in the structure. The magnitude of the structural movements is exaggerated for clarity, and some inadvisable attachment schemes are shown to demonstrate their consequences. Forces such as these must be taken into account in the design of the frame and the cladding to prevent glass breakage, panel failures, and failure of the attachments between the panels and the frame.

And the enclosure should be resilient, able to withstand infrequent, but potentially severe, exposures. In areas prone to hurricane-force winds, windows and other fenestration are made especially impact-resistant. Where buildings are at risk of flooding, they are designed to withstand the forces of floodwater and built with materials resistant to the damaging effects of temporary submersion. In locations with high security concerns, blast-resistant construction techniques and materials are used.

Resisting Gravity

Until the late 19th century, nearly all large buildings were built with exterior *loadbearing walls* made of solid brick or stone masonry. In addition to performing as building enclosure, these walls supported a substantial portion of the floor and roof loads of the building. While such walls can perform well in unconditioned buildings and can be long lasting, from a modern perspective they have limitations: They are poor thermal insulators. And they are heavy, requiring large foundations and limiting their height. (For more information about masonry loadbearing walls, see Chapter 10.)

In contemporary construction, the loadbearing masonry wall has evolved with higher-strength, reinforced masonry and the addition of thermal insulating materials, water management provisions, air barriers, and vapor retarders. These walls can be made thinner, lighter, and stronger, while performing all the functions required of a modern building enclosure. In addition, the palate of materials available for the construction of contemporary loadbearing walls has grown to include sitecast and precast concrete, steel, and wood. With all of these improvements, loadbearing exterior walls remain attractive, economical, and high-performing choices for many low- and medium-rise buildings.

The first steel-framed skyscrapers, built in the late 19th century, introduced the concept of the nonloadbearing *curtain wall*, an exterior wall supported at each story by the structural frame. The name "curtain wall" derives from the idea that the wall is thin and hangs like a curtain on the structural frame. The earliest curtain walls were constructed of masonry (Figure 16.5). The principal advantage of the curtain wall is that because it bears no vertical loads except its own weight, it can be thin and lightweight regardless of the height of the building. In comparison, a masonry loadbearing wall becomes prohibitively thick and weighty at the base of a very tall building.

For modern curtain walls, materials such as glass, aluminum, steel, and thin, reinforced concrete and masonry are favored for their

Figure 16.5
The curtain wall of Chicago's Reliance Building (1894–1895) has spandrels constructed of white terra-cotta tiles. *(Architect: Charles Atwood of Daniel H. Burnham and Company. Photo by Wm. T. Barnum. Courtesy of Chicago Historical Society ICHi-18294.)*

strength, durability, light weight, and weather resistance. Because curtain walls are used on tall buildings, they are made from noncombustible materials. They may be assembled in place from individual components or prefabricated offsite in larger sections before being transported to the construction site, lifted into position, and attached to the building frame. While the term curtain wall applies to any nonloadbearing wall enclosure system suspended from the building frame, it is sometimes used to refer more narrowly to only the metal and glass systems that are the typical enclosure of choice for the tallest buildings. In Chapter 20, we will examine curtain walls that are made of masonry and concrete. In Chapter 21, we will look at curtain walls made of metal and glass.

Constructability

Constructability—ensuring that the parts of the building can be efficiently assembled—requires attention during the design of the building enclosure due to the multitude of materials and systems that must be integrated, and in many cases, the challenges that arise from working around the outer edges of a building (Figure 16.6). There should be secure places for installers to stand, preferably on the floors of the building rather than on temporary staging or exterior scaffolding. There must be adjustment mechanisms built into the fastenings between components of the enclosure and the building frame to allow for positional inaccuracies that will be present between these systems. Sufficient clearance must be provided so that components can be installed easily, without interference by other parts, and so that workers' hands and their tools can readily reach points of attachment. And the system must be sufficiently forgiving in its design to allow for a lifetime of trouble-free performance despite the variations in workmanship and material quality that inevitably occur.

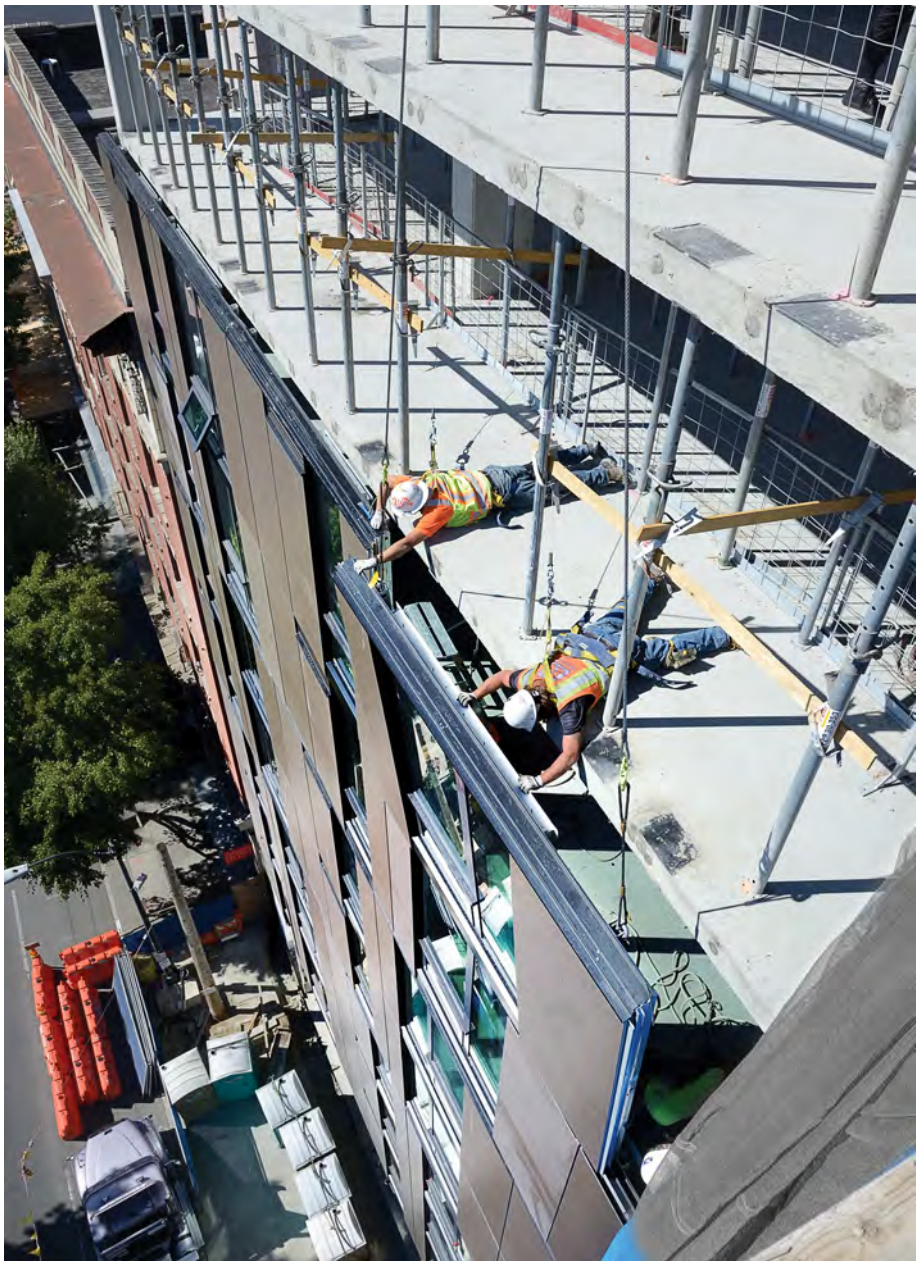


Figure 16.6

A pair of workers, safely tethered to the building frame, position a prefabricated exterior wall section as it is lifted into place. By assembling wall panels offsite, the need for exterior scaffolding on this project was eliminated and a substantial cost savings was realized. However, this approach increased demands on the single available construction crane, and scheduling of crane time became a critical path component of the construction schedule. The design of the joints between panels needed to account for inaccuracies in the locations of the concrete slab edges, permit sealing solely from the interior side, allow for movement between panels once the building was completed, and in some locations, achieve a required fire resistance rating. Paired steel weld plates, visible along the edges of the concrete slabs, are used as points of connection for the wall sections. *(Photo by Joseph Iano.)*

Sustainability and the Building Enclosure

Energy Performance

The building enclosure's most direct contribution to sustainable building comes from the thermal improvement of the building skin itself. Increased insulation levels, elimination of thermal bridging, reductions in air leakage, and thermally improved glazing systems all contribute to lower cooling and heating energy demands.

The potential energy savings are significant. For example, heat gains and losses through a commercial building enclosure designed to meet current North American energy code requirements are roughly one-third less than those of a similar building constructed in 1985 and designed to the less stringent standards of that time—a positive, yet modest improvement. However, the same building enclosure, built to today's state-of-the-art high-performance standards, can be as much as several whole times more efficient than the current minimally code-compliant design.

The building enclosure plays an important role in many passive strategies for reducing building energy consumption and improving the quality of the interior environment. Passive shading achieved through façade orientation and articulation and appropriate choices of glazing products reduces unwanted solar heat gains, increases occupant comfort, reduces visual glare, and lessens cooling loads. Strategically placed operable openings, when part of a natural ventilation strategy, reduce demands for active cooling. Windows and overhead glazing systems that provide controlled, natural daylight to the interior create a more healthful and productive interior environment, reduce reliance on electric light, and lessen interior cooling loads. Reduced air leakage through the building enclosure, in addition to saving energy, contributes to improvements in indoor air quality.

Building and Material Life-Cycle Impacts

The enclosure also plays a primary role in the durability, life span, and utility of a building. Without a well-designed enclosure that can protect the building from the elements over many decades, and which can support a healthful, productive interior environment, sustainable building is not possible.

Keeping Water Out

In order for water to pass through a building assembly, three conditions must be met simultaneously:

1. Water must be present at the face of the assembly.
2. There must be an opening through which the water can move.
3. There must be a force to move the water through the opening.

If any one of these conditions is not satisfied, then the assembly will not leak. Thus, we can use the following strategies, singly or in combination, to make the building enclosure watertight: Keep water away from the enclosure assembly, eliminate openings in the assembly, and/or neutralize the forces that can act to move water through the assembly.

Keeping Water Away

Preventing water from reaching the building enclosure is a simple and reliable strategy for keeping water out of buildings. At the building scale, steeply sloped roofs rapidly transport water off of the roof surface before that water can find its way between shingles and through fastener penetrations. Roof overhangs and canopies prevent rainwater from reaching the vertical surface of the exterior wall. Ground surfaces that slope away from the building and subdrainage systems limit the amount of water that reaches basement walls.

Within the building wall, flashings and drip edges carry water away from vulnerable openings and cause it to fall away from the wall surface. At the smallest scale, the geometry of joints between enclosure components can be manipulated such that water that penetrates the outermost layers of the assembly is redirected by sloped surfaces back to the exterior and thereby excluded from reaching more vulnerable parts.

Eliminating Openings

When roofs are pitched at low slopes, a continuous roofing membrane—fully watertight and free of any openings—is used so that even standing water ponded on top of the membrane cannot pass through. Such membranes must be installed with sufficient care to prevent even small gaps at seams and edges, and around penetrations for piping, roof openings, and such. The membrane material must also be sufficiently durable to remain leak-free over many years, even with sustained exposure to the sun's damaging rays, occasional foot

traffic, and large daily and seasonal changes in temperature.

Similarly, below-grade foundation waterproofing membranes function as continuous, gap-free, waterproof barriers. Unlike exposed roof membranes, those below grade are protected from the sun's rays and are subjected to less extreme temperature fluctuations. On the other hand, if leaks do occur, gaining access to below-grade waterproofing to make repairs can be much more costly and disruptive compared to the effort required for exposed roof membranes.

Barrier Walls

Exterior above-grade walls that rely on the elimination of openings as the primary strategy for keeping water out are called *barrier walls* (Figure 16.7*A*). Examples include precast concrete and glass-reinforced concrete curtain walls (Chapter 20), tilt-up concrete (Chapter 14), and insulated metal wall panels (Chapter 21). These may also be called *face-sealed walls* because the water barrier is located at the exterior face of the wall. Figure 21.24 illustrates a faced-sealed, metal insulated panel barrier wall system.

With face-sealed barrier walls, the most vulnerable part is often the joints between wall panels. These must remain as perfectly watertight as possible, maintain flexibility to absorb movements between panels, and withstand all of the stresses of the exterior environment to which they are permanently exposed. For these reasons, as an alternative to face-sealed joints, barrier wall systems may rely on multistage joints designed with more complex strategies for keeping water out. (See, for example, Figure 20.12.)

Mass Walls

A *mass wall* (Figure 16.7*B*) is a semipermeable barrier wall that allows water to enter through small openings or pores. However, because of the thickness and density of the wall, moisture can be stored safely within it for some time and then gradually released back to the exterior (or sometimes the interior) through evaporation. Traditional solid masonry walls constructed without a cavity (see Chapter 10) function as mass walls. Modern masonry and site-cast concrete walls, to the extent that they are constructed without drainage provisions or face-sealed coatings, also may function as mass walls.

Neutralizing the Forces That Move Water

The third strategy for keeping water out of the building enclosure is to neutralize the forces that move water through openings in the assembly. This strategy is commonly applied in the design of exterior walls, as illustrated in concept in Figure 16.8.

Wherever there are possible points of water entry through the building enclosure, the techniques for counteracting the first four forces illustrated in the Figure 16.8 are relatively straightforward to implement, mainly by manipulating the geometry of the joint or opening. Neutralizing the fifth force, air pressure, is done by creating an airtight boundary behind the opening. In this way, air pressure within the opening can quickly equalize that at the exterior, and sustained airflows that could otherwise transport water through the opening are prevented. In idealized form, this strategy for neutralizing air pressure differences is called *pressure-equalized design*. In practice, varying degrees of pressure equalization may occur within an opening or assembly.

Most wall enclosure systems that employ strategies for neutralizing the forces that move water through the assembly also employ concealed barriers as a final line of defense against water leakage. In fact, continuous water-resistant and airtight boundaries are essential parts of most exterior wall assemblies. And as we

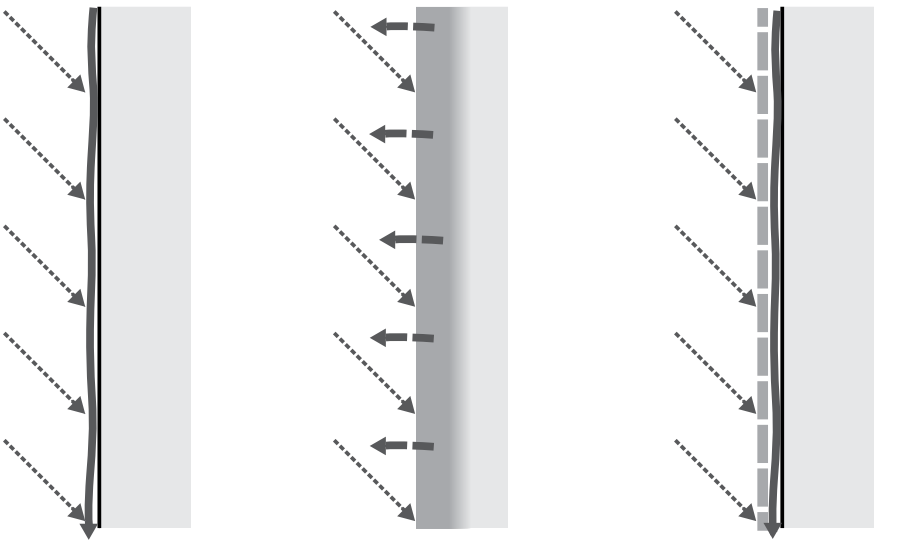


FIGURE 16.7
Three types of exterior walls. (*A*) Barrier walls prevent water ingress by eliminating or sealing all openings in the wall. (*B*) Mass walls allow water into the wall, where the water is temporarily stored until it can evaporate back out. (*C*) Drained cladding includes a drainage space behind the exterior cladding. Water that penetrates the cladding layer is captured in the drainage space and then directed back out. In practice, exterior walls frequently combine features of two or three of these types. For example, as a second line of defense against water intrusion, drained cladding walls usually include a water barrier layer at the back of the drainage cavity.

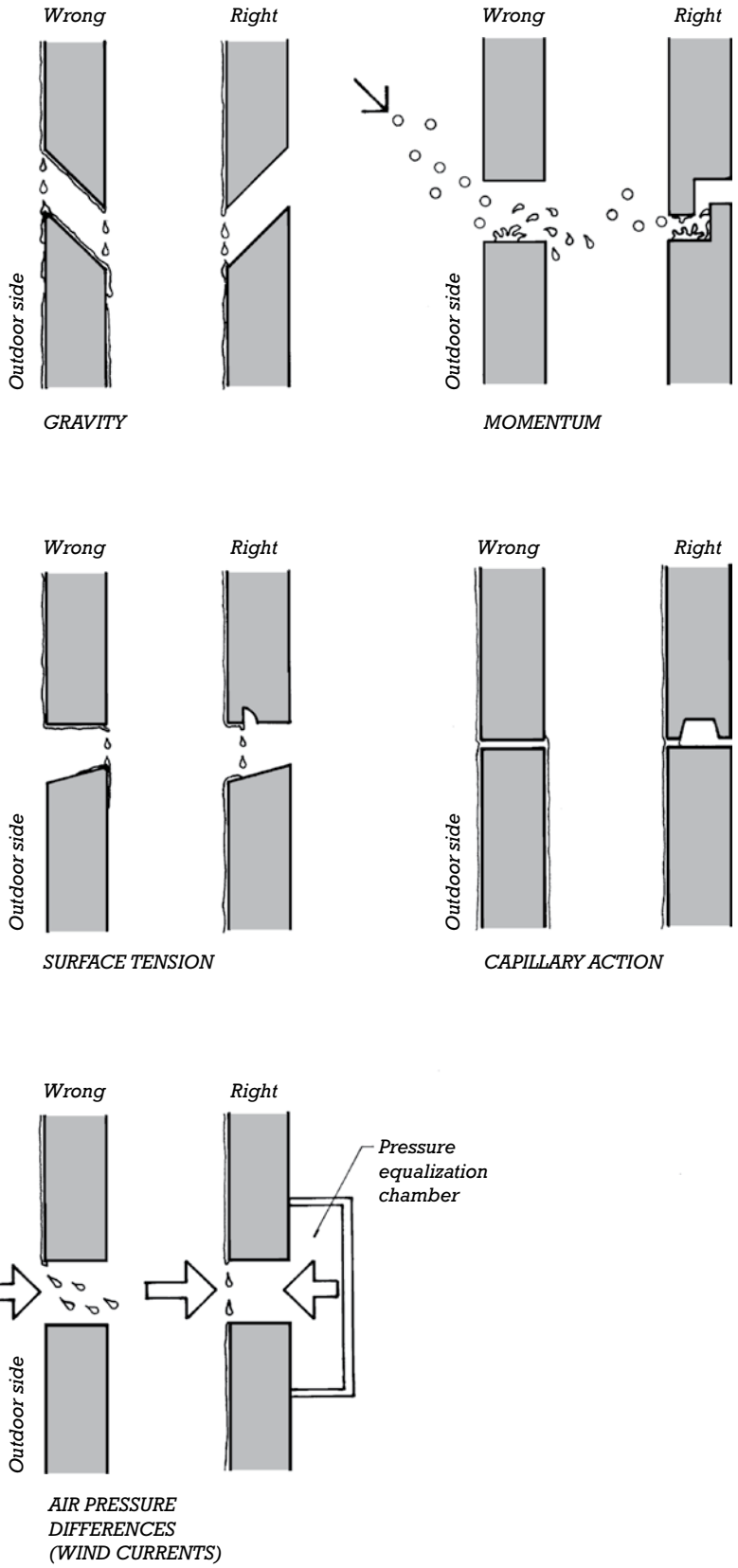


FIGURE 16.8

The five forces that can move water through an opening in the building enclosure—*gravity*, *momentum*, *surface tension*, *capillary action*, and *air pressure*—are illustrated in cross section with the outdoor side to the left. Each pair of drawings shows (*left*) a horizontal joint between wall panels in which a force moves water through the joint and (*right*) an improved design for that joint that neutralizes this force. Leakage caused by gravity is avoided by sloping internal surfaces of joints toward the outside; such a slope is called a *wash*. Momentum is counteracted with baffles or labyrinth-like geometry within the joint. Drips and capillary breaks stop leakage caused by surface tension and capillary action, two closely related forces. Water pushed by moving air is counteracted by creating airtight boundaries that neutralize air pressure differences across the enclosure assembly.

will see later in this chapter, airtight boundaries are also important for reducing energy losses in buildings, controlling condensation, and more.

Drained Cladding, Rainscreen Cladding, and Cavity Walls

Drained cladding (also called *rainscreen cladding*) (Figure 16.7*C*) consists of an exterior cladding, a drainage space behind the cladding, and a concealed air and water-resistive barrier behind the drainage space. Drained cladding combines the strategies of minimizing openings and neutralizing forces to keep water from penetrating the wall.

The traditional masonry *cavity wall* is an example of drained cladding. In such walls, the outer masonry veneer is separated from the backup wall by a vertical cavity an inch (25 mm) or more in depth. The forces of momentum and air pressure are resisted primarily by the veneer. Water that penetrates the veneer is prevented from crossing the cavity as surface tension and capillary action are neutralized by the open cavity space. Gravity is exploited to drain water down the cavity and outward to the exterior over flashings and through weep holes at the cavity bottom. A water-resistant coating or membrane on the face of the backup wall serves as a concealed water barrier and last line of defense against water penetration. This membrane also acts as an air barrier to control air leakage. Figures 20.1 and 20.3 illustrate brick veneer cavity wall construction.

Drainage spaces of virtually any depth can be created in drained cladding. Water-resistant membranes that have been "crinkled" or that have small plastic dimples adhered to their surface create voids as narrow as approximately 1/16 inch (1 mm). Thicker plastic drain mats inserted behind cladding are used to create spaces up to roughly 3/8 inch (10 mm) deep. And furring systems made from wood, metal, or plastic can be used to create spaces of greater depths.

Deeper drainage spaces tend to improve drying in the assembly. Spaces approximately 3/8 inch (10 mm) or deeper are sufficient to neutralize surface tension and capillary forces, allowing water to drain as freely as possible. A space at least this deep also promotes greater air movement and moisture evaporation. When open only at the bottom, such a space is described as *vented*, and when open at the bottom and at the top of the wall, as *ventilated*. The continuous flow or air through a ventilated drainage space improves evaporation and provides greater drying potential compared to a vented cavity, which is open only at the bottom.

The principles of drained cladding are frequently applied in the design of joints within cladding systems as well. See, for example, the precast cladding panel joint in Figure 20.12 or the storefront and curtain wall sections in Figures 21.11 and 21.12.

Water-Resistive Barriers

Drained cladding walls include a concealed surface that serves as the drainage plane, or *water-resistive barrier* (*WRB*), to resist the passage of water further into the assembly. Traditionally, asphalt-saturated building felts or papers applied over the wall sheathing were commonly used for this purpose. More recently, these products have been mostly replaced by a variety of synthetic membrane products offering a broader range of characteristics suitable to walls with different requirements. Synthetic house wraps and building wraps are stapled to the wall sheathing in the same way as traditional building felts but offer greater durability and resistance to air leakage. Self-adhered sheet membranes, in which one side of the material is coated with a pressure-sensitive adhesive, form a continuous bond with the face of the wall sheathing, as do membranes that are applied in liquid form and cured in place. Some sheathing products, such as plastic foam insulation boards, specially coated wood panels, or glass-mat-faced gypsum sheathing, when combined with appropriate sealing tapes and mastics, can also act as water-resistive barriers.

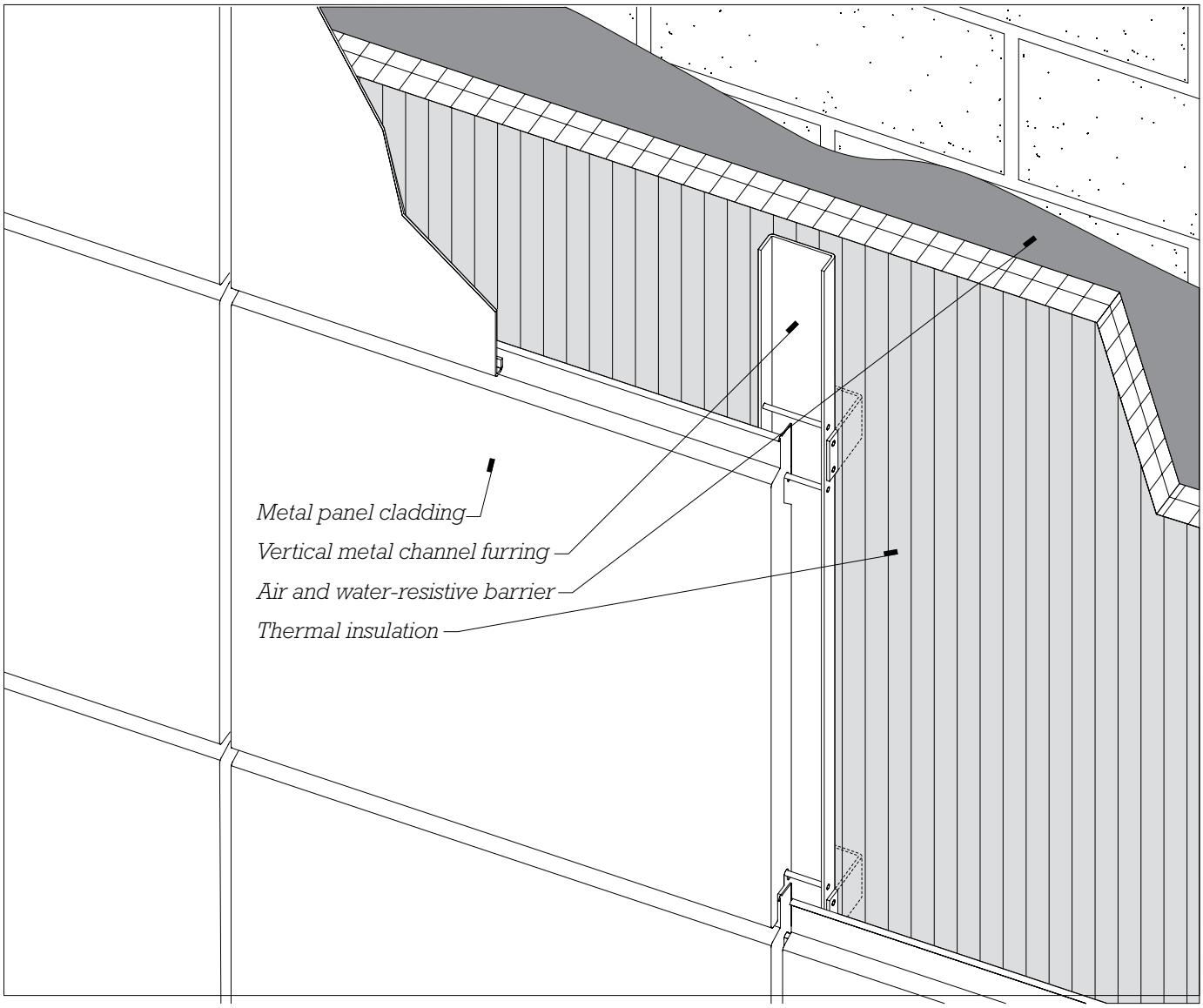
A Drained Cladding Wall Design

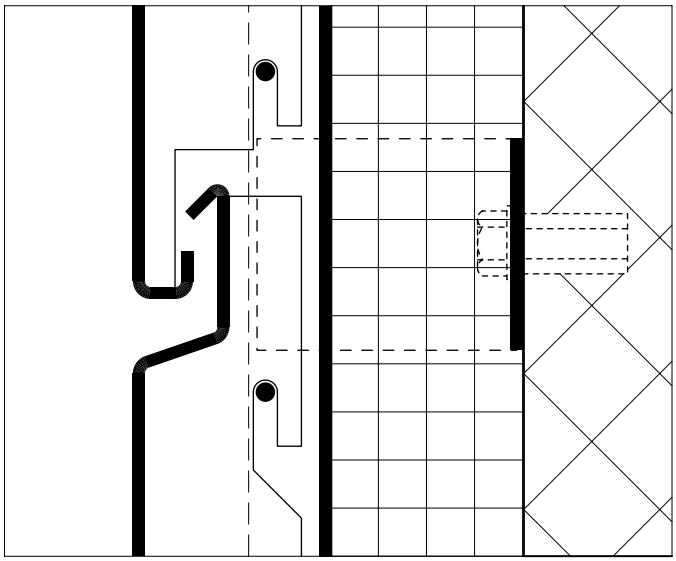
Figure 16.9 depicts a drained cladding system design. First, the face of the concrete masonry backup wall is coated with a water-resistant and air-impermeable membrane. Metal U-shaped clips are fastened to the wall and insulation panels are adhered to the wall, with the clips projecting through the insulation. Vertical metal channels are bolted to the clips. Finally, the metal panels are hung from horizontal rods within the channels. The space between the metal panels and the insulation functions as the drainage space. Water that passes through the panel joints drains downward and then is carried back out of the wall by flashings at each floor level (flashings not shown).

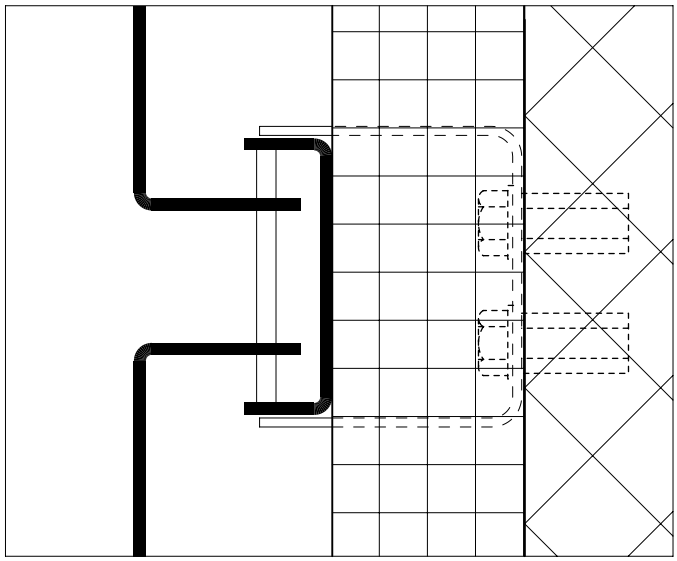
This design also exploits techniques for counteracting the forces that move water. Note the absence of sealants or gaskets at the metal panel joints. The panels are separated by generous gaps that preclude capillary movement of water, provide installation tolerances, and allow for expansion and contraction. All four edges of the panels are shaped as labyrinth joints. The forces of surface tension and gravity are counteracted by sloping surfaces (washes) and drips. Reasonably airtight

FIGURE 16.9

An open-jointed drained cladding wall system. To reduce thermal bridging at the U-shaped clips, insulating spacers (not shown) can be installed between the clips and the backup wall. *(Design by Wallace Floyd Associates, Bechtel/Parsons Brinckerhoff, Stull and Lee, Gannett Fleming/URS/TAMS Consultants, and the Massachusetts Highway Department.)*


Metal panel cladding
Vertical metal channel furring
Air and water-resistive barrier
Thermal insulation





compartments are created behind the open joints, bounded by the vertical metal channels, flashings at each floor level (not shown), and the air and water barrier membrane coating on the face of the backup wall. As a result, sufficient pressure equalization is achieved to minimize forceful airflows through the joints.

Controlling the Flow of Heat

Thermal insulation is material added to the building enclosure to slow the conduction of heat through the assembly. Insulation is installed in roofs and exterior walls, in floors over unheated spaces, around foundations, under concrete slabs on grade, and wherever else conditioned (heated or cooled) space comes in contact with unconditioned space, the earth, or the outdoors. It reduces unwanted heat losses in the winter and unwanted heat gains in the summer. A well-insulated building enclosure increases occupant comfort and reduces the energy required to heat and cool the building.

Thermal Insulation

A material's effectiveness in resisting the conduction of heat is called its *thermal resistance*, abbreviated *R*, and expressed with units ft²-hr-°F/BTU. In the metric system, thermal resistance is abbreviated as *RSI* (or sometimes also simply as R), with units m²-°K/W. The higher a material's R-value, the higher its resistance to heat flow and the better its performance as a thermal insulator. Most insulation materials are lightweight and porous and work by trapping air within many very small spaces within the material. Some examples of insulating materials, exhibiting a range of properties, are listed in Figure 16.10. For purposes of comparison, thermal resistance values for some common building materials are listed as well.

Insulation Type and Method of Installation	Material	R-Value[a]	Combustibility	Comments
Batt/blanket: Installed between framing members and held in place either by friction or by a facing stapled to the framing, or pinned in place	Glass and mineral fiber	2.9–4.4 *20–31*	Noncombustible; added facings may be combustible	Low in cost, easy to install
Semirigid board: Mechanically fastened or adhered in place	Mineral fiber	3.6–4.2 *25–29*	Noncombustible	Can be exposed to moisture in an exterior wall drainage cavity
Rigid board: Mechanically fastened or adhered in place	Expanded and extruded polystyrene	3.2–5.0 *22–35*	Combustible; releases toxic gasses when burned	Can be used in contact with earth or exposed to moisture in a drainage cavity
Spray foam: Foamed in place	Open- and closed-cell polyurethane	3.7–7.1 *26–49*	Combustible, releases toxic gasses when burned	Air-impermeable, closed-cell foams are vapor-permeable
Blankets: Stapled or pinned	Aerogel	8.0–10 *55–69*	Noncombustible	High R-value, very expensive
Vacuum panel	Sandwich panel with precipitated or fumed silica core	28–39 *190–270*	Noncombustible	Very high insulation value, high cost, requires special care during installation
Approximate insulating values of some common construction materials	Softwood	1.0 *7*		
	Concrete	0.1 *0.7*		
	Steel	0.003 *0.02*		
	Aluminum	0.0007 *0.005*		

[a] R-values are per unit of thickness, expressed first in inch-pound units of ft²-hr-°F/BTU-in. and second in metric units (italicized) of m²-°K/W-m. For example, for an insulation material with R-values of 5 ft²-hr-°F/BTU-in. (35 m²-°K/W-m), 3 inches (76 mm) of the material would have a total insulation value of 5 ft²-hr-°F/BTU-in. × 3 in. = R-15 or 35 m²-°K/W-m × 0.076 m = RSI-2.7.

Figure 16.10

Insulation materials representing a range of types, materials, and thermal properties. A few construction materials are also included for comparison. For more information about rigid insulation materials for low-slope roofs, see Figure 17.5.

A limitation in the current standards for determining thermal resistance of building insulation materials is that these standards do not account for variations in insulation performance at different temperatures. In fact, the thermal resistance of insulating materials can vary by as much as 10 to 25 percent with changes in ambient temperature. Additionally, for some insulation materials, thermal resistance increases at colder temperatures, while for others, thermal resistance decreases.

Insulated Enclosure Assemblies

The thermal performance of an assembly depends on the combined insulating properties of the materials within it. Every material contributes in some measure to the overall thermal resistance, the amount depending on the material, its thickness, and its arrangement within the assembly.

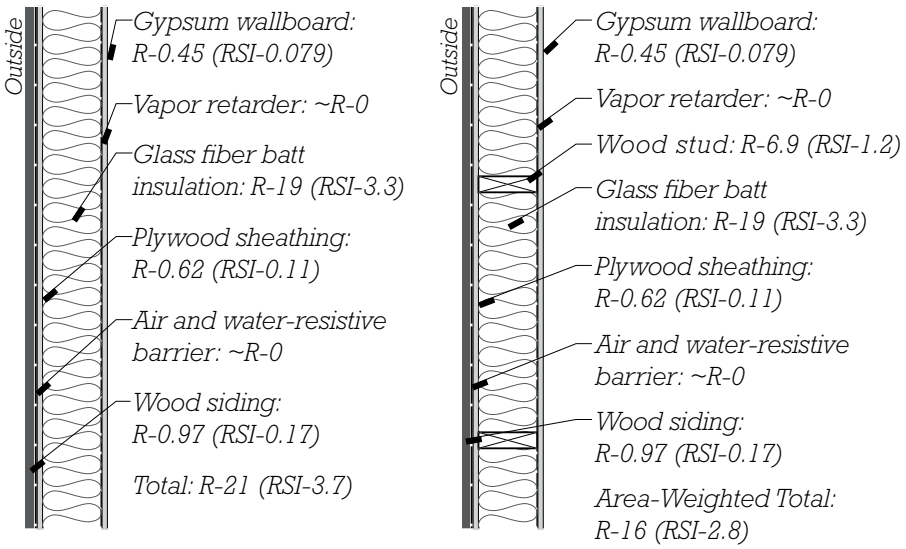
Figure 16.11 illustrates examples of exterior wall R-value calculations. Each layer of material in the wall contributes to the wall's total thermal resistance, with the largest contribution coming from the insulation material itself. This kind of calculation is most simple if solid framing members within the wall are ignored and the wall is treated as a sandwich of homogenous layers, as in (*A*) in the figure. In this case, the total thermal resistance of the wall is the sum of the resistances of each layer, or approximately R-21 (RSI-3.7).

In Figure 16.11*B*, the effects of the wood framing are included in the R-value calculations. Because solid wood members have a lower thermal resistance than the insulation they displace, these parts of the wall will also have a lower resistance. To obtain a realistic value for the wall as a whole, the resistances of the different wall areas are combined proportionally. If, overall, 25 percent of the wall area is made up of solid framing, the average thermal resistance of the wall as a whole is approximately R-16 (RSI-2.8), a reduction of one-quarter of the value found in (*A*).

Thermal Bridging

In Figure 16.11*B*, wood framing within the insulated wall acts as a *thermal bridge*. A thermal bridge is any material with a relatively low thermal resistance (or high *thermal conductivity*, the opposite of thermal resistance) that provides a shortcut for heat flow through an insulated assembly. Even when thermal bridges make up a relatively small portion of an assembly's area, their low resistance to the flow of heat means they can significantly reduce thermal efficiency.

Because the thermal conductance of steel is even higher than that of wood, the effects of thermal bridging can be especially severe in metal-framed assemblies. If the wood studs in Figure 16.11 are replaced with light gauge metal (Figure 16.12*A*), the overall R-value of the wall is reduced even further, to approximately R-6.9 (RSI-1.2). The thermal inefficiency of metal framing is addressed in contemporary energy codes, which require *continuous insulation* in many such assemblies. Continuous insulation, usually rigid or semirigid boards, is located to one side or the other of the framing. In this way, the thermal shortcuts created by the framing are interrupted, the energy losses are reduced, and the thermal resistance of the assembly as a whole is improved. (Figure 16.12*B*). As discussed later in this chapter, continuous insulation, when placed on the exterior side of a framed enclosure assembly, also better protects the framing from the risks of condensation within the framing cavity.



(A) THERMAL RESISTANCE IGNORING FRAMING

(B) THERMAL RESISTANCE INCLUDING WOOD FRAMING

FIGURE 16.11
Thermal resistance calculations for a wood-framed wall. In (*A*), the effects of the wood framing are ignored. In (*B*), the lower thermal resistance of the wood framing is included in the calculations.

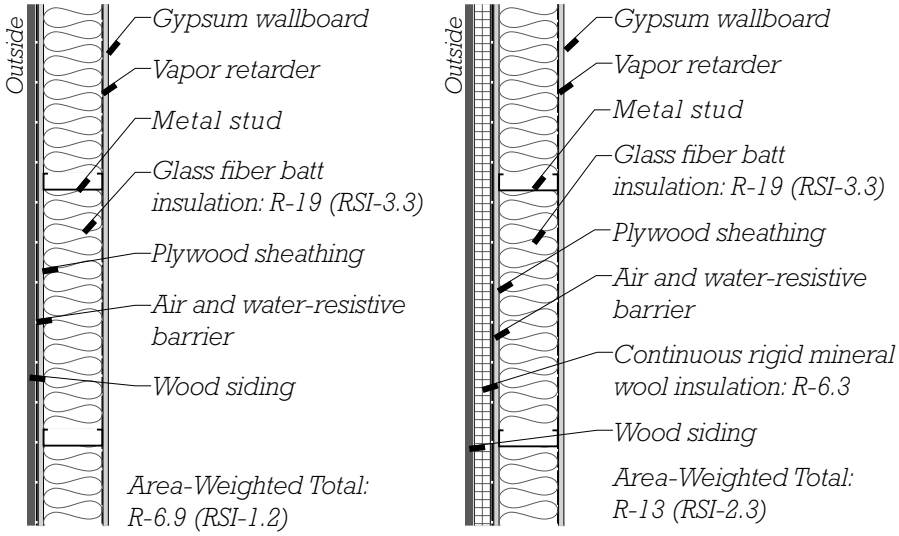


FIGURE 16.12
Thermal resistance calculations for a metal-framed wall. In (*A*), the effect of the thermal bridging at the metal framing dramatically lowers the overall thermal resistance. In (*B*), continuous insulation is used to interrupt the thermal bridging and improve the overall thermal resistance.

Thermal bridging is also frequently a concern where different construction assemblies meet. For example, extra care to ensure continuity of thermal insulation is often required where foundations meet above-grade walls, walls meet floors and roofs, exterior balconies connect to interior building structure, and openings meet opaque wall areas.

Radiant Heat Barriers

Thermal radiation can also contribute to heat flows through enclosure assemblies. It occurs whenever there is a temperature difference across open air spaces within such assemblies, such as in drainage or ventilation cavities within walls or roofs. *Radiant barriers* are shiny, metallic foils or membranes with low *emissivity*. When placed on one side or the other of an open space, they greatly reduce the emission or absorption of thermal radiation. Due to the physics of radiant transfer, radiant barriers are most effective when there is a high temperature difference across the space. See Chapter 7 for more information about radiant barriers in residential enclosure assemblies.

Controlling Air Leakage

Air can move through the building enclosure wherever air pressure differences exist between one side of the assembly and the other. Air pressure differences are created by wind acting on the external surfaces of a building, by *stack effect* (the tendency of tall buildings to act like chimneys, drawing air in at either the top or bottom and expelling it at the other end), and by the building mechanical equipment, including its air-handling systems and exhaust fans (Figure 16.13). Unintended air leakage can increase energy losses, lead to moisture accumulation within the building enclosure, and degrade indoor air quality.

Air Barriers

Materials that resist the passage of air are called *air barriers*. Examples include building wraps, gypsum wallboard, plastic sheets, spray foam insulation, various specialized membranes applied to the face of wall sheathing, sealants, tapes, and more. To function as an air barrier, a material must be resistant to the passage of air, it must have sufficient strength and rigidity to withstand the air pressure differentials acting on it, it must be able to accommodate movement where it spans joints, and it must be durable enough to perform its functions for the life of the building.

The greater a material's resistance to the passage of air, the lower its *air permeance* and the better its performance as an air barrier. Air permeance is expressed in units of cfm/sf@1.57 psf or L/s-m^2@75 Pa. The most commonly cited standard for air barrier materials requires an air permeance of not greater than 0.004 cfm/sf@1.57 psf (0.02 L/s-m^2@75 Pa) (Figure 16.14).

Air Barrier Assemblies and Systems

When air barrier materials are used in combination within walls, roofs, and floors, they are called *air barrier assemblies*. Because flawless, continuous sealing between materials is never possible, air permeance requirements for air barrier assemblies are less stringent than those for individual

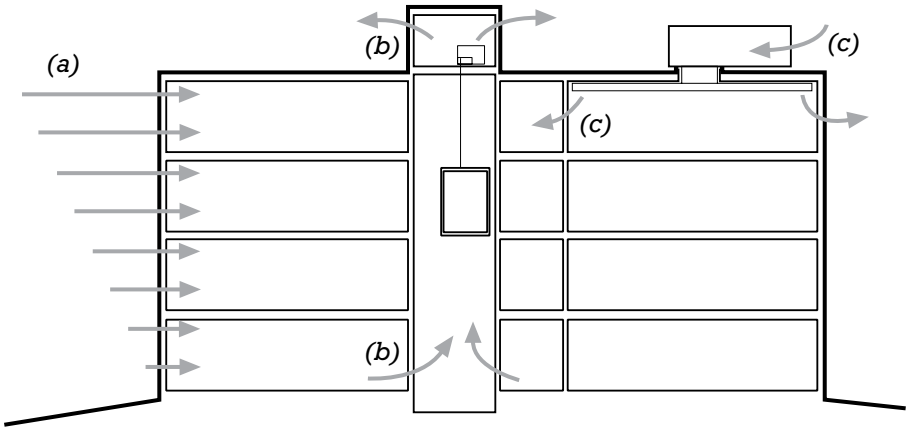


FIGURE 16.13
Air pressure differences in a building can be caused by (*a*) wind, (*b*) the stack effect, such as within an elevator shaft, and (*c*) building mechanical systems.

Material	Air Permeance	
	cfm/sf@1.57 psf	L/s-m²@75 Pa
Polyethylene sheet, 6 mil (0.15 mm)	~0	~0
Aluminum foil, 1 mil (0.025 mm)	~0	~0
Self-adhered modified asphalt membranes	~0	~0
Plywood, ⅜ in. (9.5 mm)	~0	~0
Extruded polystyrene rigid foam insulation, 1½ in. (38 mm)	~0	~0
Most low-slope roofing membranes	~0–0.002	~0–0.01
High-density spray polyurethane foam insulation, 1½ in. (38 mm)	0.0002	0.001
Fluid-applied, vapor-permeable air barrier membrane	<0.0004	<0.002
Nonperforated polyolefin building wrap		
Commercial grade	0.001	0.005
Residential grade	0.007	0.036
Low-density spray polyurethane foam insulation, 3 in. (75 mm)	0.002–0.32	0.01–1.6
Gypsum wallboard, ½ in. (12 mm)		
Exterior sheathing	0.002	0.0091
Interior wallboard, unpainted	0.004	0.0196
Oriented strand board, ⅜ in. (11 mm)	<0.004	<0.02
Asphalt roofing felt, #30	0.037	0.1873
Asphalt building felt, #15	0.078	0.3962
Glass fiber batt insulation	7.3	37
Cellulose insulation, sprayed	17	87

FIGURE 16.14
Approximate air permeance of materials. Shaded rows indicate materials exceeding recommended air permeance for air barrier materials.

materials and are typically in the range of 0.01 to 0.04 cfm/sf@1.57 psf (0.05 to 0.2 L/s-m²@75 Pa).

To effectively control air leakage into and out of a whole building, its conditioned space must be completely surrounded by combinations of air barrier assemblies and materials, creating an uninterrupted *air barrier system* capable of resisting air pressure differentials acting anywhere across the conditioned boundary of the building. Careful attention to design details and quality of construction is required to create such complete systems of enclosure. All potential discontinuities—gaps between panels, laps in sheet materials, transitions between dissimilar substrates, fastener penetrations, movement joints, penetrations for structure or services, installation space around window and doors frames, junctions between foundation, wall,

and roof assemblies, gaps between operable doors and windows and their frames, and so on—must be made as airtight as possible. The International Energy Conservation Code and the Canadian National Building Code both include standards for maximum permitted air leakage through whole building air barrier systems.

Air Barrier Location

Air barrier materials can be located anywhere within an assembly as long as they form an interconnected, continuous system. At the inside surface of the building enclosure, the airtight drywall approach and simple caulk and seal are air barrier systems consisting of gypsum wallboard combined with tapes, sealants, and gaskets to seal leakage paths around wallboard penetrations and between framing members (see Chapter 7). These systems are relatively easy and inexpensive to install, making them especially popular for residential construction. They are less favored for commercial buildings, where frequent changes to interior partitions, finishes, and wiring make it unlikely that the continuity of a system depending on the careful detailing of these elements will be maintained over the life of the building.

Plastic sheeting has low air permeance, and when used as a vapor retarder behind gypsum wallboard, can act as an air barrier. However, difficulty in sealing the plastic sheet seams and penetrations, as well as a tendency for the plastic to stretch and deflect between supporting framing, limit this material's suitability in air barrier applications, especially for taller buildings or anywhere else high air pressure differentials are expected.

Toward the middle of a building enclosure assembly, foam insulation can be sprayed into the space between studs, joists, and rafters, acting as part of an air barrier in combination with caulks or sealants to seal leakage paths around the framing members.

Toward the outside of the building enclosure, air barrier materials are installed over sheathing in framed construction or on the exterior face of masonry or concrete backup walls (for example, see Figure 16.9). Building wraps and plywood or gypsum board sheathing panels themselves, and fluid-applied or adhered sheet membranes, may all be used in combination with various sealing or taping materials. In this location, air barrier materials are easy to install, with a minimum of complex intersections. Where penetrations occur for the anchoring of cladding or sheathing, they are sealed to ensure airtightness. In this location, these materials also frequently serve as water-resistive barriers in the assembly, and may be referred to as an *air and water-resistive barrier* (*AWB*), or sometimes, simply, *air-weather barrier*.

Air Barriers and Moisture Control

When air passes through a building assembly, water vapor in the air is transported with it. By preventing the flow of warm, moist air to the cooler side of a building assembly where moisture condensation can occur, air barriers play an important role in protecting against moisture accumulation within the assembly.

Controlling the Diffusion of Water Vapor

Air always contains some water in the form of *water vapor*, an invisible gas. The amount of water vapor in the air can be described as the *relative humidity*. For example, at 50 percent relative humidity, air contains half of the maximum amount of water vapor that it is capable of holding. Air feels dry when its relative humidity is low and clammy when its relative humidity is high.

The relative humidity of air changes with the air's temperature, even when the amount of water vapor stays the same. For example, if air has a relative humidity of 50 percent and we start to cool the air, its relative humidity starts to increase. This is because as the air cools, its capacity to hold water is reduced. Eventually, if we cool the air to a low enough temperature, it reaches 100 percent relative humidity. If the air is cooled any further, the water vapor starts to turn to liquid, a process called *condensation*. The temperature at which air reaches 100 percent relative humidity is also called its *dew point temperature*. In other words, any time air is cooled below its dew point, condensation will occur.

Condensation can take place in buildings in many different ways. In winter, room air circulating against a cold pane of glass may be cooled below its dew point, and water droplets will form on the glass. If the air is very humid, the droplets will grow in size then run down the glass to accumulate in puddles on the windowsill. If the glass is very cold, the condensate may freeze into patterns of ice crystals on the glass. In a similar fashion, on a hot, humid summer day, water vapor in the air may condense on the surface of a cold-water pipe, a cool basement wall, or an ice-cold glass of lemonade. Hidden from view, condensation can also occur within the walls, roofs, and other assemblies that enclose a building.

Water Vapor Diffusion in Building Assemblies

Water vapor is a gas and exerts pressure, called *vapor pressure*. The more water vapor an air mass contains and the higher the air temperature, the greater the vapor pressure. Under wintertime heating conditions, the air inside a building is at a higher temperature and contains more water vapor than the air outside. The result is a net difference in vapor pressure acting from inside to outside, causing water vapor to diffuse outward directly through the various solid material layers of the enclosing assembly. If the

rate of diffusion is high enough and the drop in temperature within the assembly great enough, the air within the assembly will reach its dew point and condensation will occur.

Under summertime cooling conditions in hot, humid weather, the diffusion of water vapor through the building enclosure is reversed. Water vapor is driven from the warm, damp outside air toward the cooler, drier air within the building. In most of North America, this summer condition is not as severe as that in winter: Differences in summer temperature between indoors and outdoors are not as great as those in winter, and the cooling season is short compared to the heating season. Where heating conditions predominate, control of water vapor in building assemblies focuses primarily on the flow of vapor from interior to exterior. In areas of the American South and in the Hawaiian Islands, the summer condition is the more severe, and the flow of water vapor from exterior to interior is the problem that receives more attention.

Vapor Retarders

A *vapor retarder* is a material used to slow the diffusion of water vapor through a building assembly. Vapor retarders are continuous sheets, boards, or coatings made of plastic, metal foil, coated paper, or other materials resistant to the passage of water vapor.

The greater a material's resistance to water vapor diffusion—that is, the lower its *vapor permeance*—the more effective it is as a vapor retarder. Vapor permeance is measured in *perms* and expressed either in the unit grains/hr-ft^2-in. Hg or g/s-m^2-Pa. One U.S. perm equals 5.72×10^{-8} metric perms. To arrive at more workable units, metric perms may be expressed as nanograms (billionths of a gram) of water and rounded to fewer significant digits. For example, one U.S. perm may be equated to 60 ng/s-m^2-Pa.

In the International Building Code, vapor retarders are classified according to their relative permeance. Class I vapor retarders are the most resistant to vapor diffusion, having a vapor permeance of 0.1 perm (6 ng/s-m^2-Pa) or less. Class II vapor retarders may have a permeance as great as 1 perm (60 ng/s-m^2-Pa) and Class III vapor retarders as great as 10 perms (600 ng/s-m^2-Pa). Because of their very high resistance to vapor diffusion, Class I vapor retarders may also be referred to as *vapor barriers*.

Commonly used vapor retarder materials include polyethylene plastic sheet, kraft paper facing on glass fiber batt insulation, aluminum foil facing on various types of insulation, and specially formulated paint primers with low vapor permeance. Closed-cell foam insulation can also act as a vapor retarder, depending on its thickness (Figure 16.15).

In some materials, vapor permeance can change. Materials that absorb moisture, such as plywood or the kraft paper facing frequently accompanying glass fiber batt insulation, tend to increase in permeance with increases in humidity. Some proprietary membranes are engineered purposely to increase in permeance under conditions of high humidity or to have different rates of permeability in different directions through the membrane. Such variable permeance (or "smart") vapor retarder materials can act to inhibit unwanted vapor diffusion into an assembly under normal conditions while enhancing the ability of the assembly to dry outward if excess moisture accumulates within it.

Vapor Retarder Usage

When used, vapor retarders are located toward the warmer side of the insulation in a building assembly. In this position, they slow the diffusion of water vapor into the assembly from the side of higher vapor pressure, limiting chances for dew point conditions and condensation to occur within the assembly's cooler portions.

Vapor retarders become increasingly important as the difference in temperature increases on opposite sides of the enclosure, as this also makes the risk of condensation within the assembly greater. For example, North American model building codes require Type I or II vapor retarders on the interior warm side of enclosure assemblies for roughly the upper half to two-thirds of the continental United States and all of Canada. In these regions, the cold winter season creates a sustained condition for many months in which condensation can occur within enclosure assemblies unless the rate of vapor diffusion from the warm interior is slowed (Figure 16.16).

Vapor retarders are also important when enclosing high-humidity spaces, such as indoor swimming pools, or museum galleries in which relative humidity is kept high to protect artwork. With higher interior humidity levels and higher dew points, the potential for condensation within the enclosure also increases.

The purpose of a vapor retarder is to keep moisture out of the assembly. But, a vapor retarder can also become an impediment to drying if an assembly becomes overly damp. For example, an exterior wall in a cold climate may experience significant water vapor drive from the exterior inward in the summer. Or, exterior water may leak into a wall any time of the year through defects in its water control layers. In circumstances such as these, a vapor retarder can unintentionally entrap moisture and increase the risks of mold and mildew growth or decay.

In practice, the choice of vapor retarder material and placement, and even whether to use a vapor retarder at all, must consider the various conditions to which the assembly may be exposed, along with the following:

- Vapor retarders with a lower permeability should be avoided where one with a higher permeability is sufficient.

• Where vapor retarders are used, the cooler side of the assembly, opposite the vapor retarder, should remain vapor-permeable (or "breathable"). For example, building wraps and other wall water barrier membranes are usually formulated to be vapor-permeable for this reason.

• In hot, humid regions, interior vapor retarders should be avoided. For example, in such a climate, vinyl wallpaper (a material with low vapor permeance) applied to the interior side of exterior walls can lead to moisture entrapment and mold and mildew growth beneath the vinyl.

• In mild or balanced climates, or where assemblies are designed to minimize the risks of condensation (see Figure 16.17), no vapor retarder may be needed.

• Where vapor control and high drying potential are both important, consider vapor retarder materials that change

	Vapor Permeance		
	U.S. Perms grains/hr-ft²-in. Hg	Metric Perms[a] ng/s-m²-Pa	Class
Aluminum foil, 1 mil (0.025 mm)	~0	~0	I
Self-adhered bituminous flashing and waterproofing membranes	0.05	3	I
Polyethylene sheet, 4 mil (0.08 mm)	0.08	4.8	I
Paint, exterior alkyd (oil), three coats over wood	0.3–1.0	18–60	II
Kraft paper facing for glass fiber batt insulation			
Low humidity	<1	<60	II
High humidity	<10	<600	III
Paint, latex vapor barrier primer	0.5	30	II
High-density, closed-cell spray polyurethane foam, 2 in. (50 mm)	0.6	36	II
OSB sheathing, 7/16 in. (11 mm) thick			
Low humidity	0.5	30	II
High humidity	3	180	III
Plywood sheathing, ½ in. (12 mm) thick			
Low humidity	0.5	30	II
High humidity	15	900	n/a
Extruded polystyrene rigid foam, 1 in. (25 mm)	1	60	II
Proprietary variable permeance membranes			
Low humidity	<1	<60	II
High humidity	>10	>600	n/a
Paint, interior alkyd, interior primer plus one flat finish coat over plaster	1.6–3.0	96–182	III
Gypsum wallboard, ½ in. (12 mm) thick			
Painted, interior latex	2–3	120–180	III
Unpainted	25	1500	n/a
Building paper, asphalt-impregnated felt			
Low humidity	2–5	120–300	III
High humidity	60	3600	n/a
Expanded polystyrene foam, 1 in. (25 mm)	3	180	III
Housewraps			
Low permeance	5–10	300–600	III
High permeance	10–50	600–3000	n/a
Low-density, open-cell spray polyurethane foam insulation, 2 in. (50 mm)	17	1020	n/a

[a]*Conversions are rounded such that 1 U.S. perm = 60 metric perms.*

FIGURE 16.15
Vapor permeance of common building materials. Values are approximate and may vary between products from different manufacturers. Class designations are according to IBC criteria, as explained in the accompanying text. Materials in shaded rows have permeance too high to be considered vapor retarders.

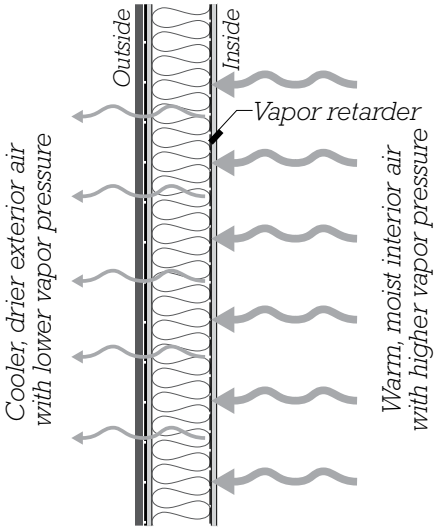
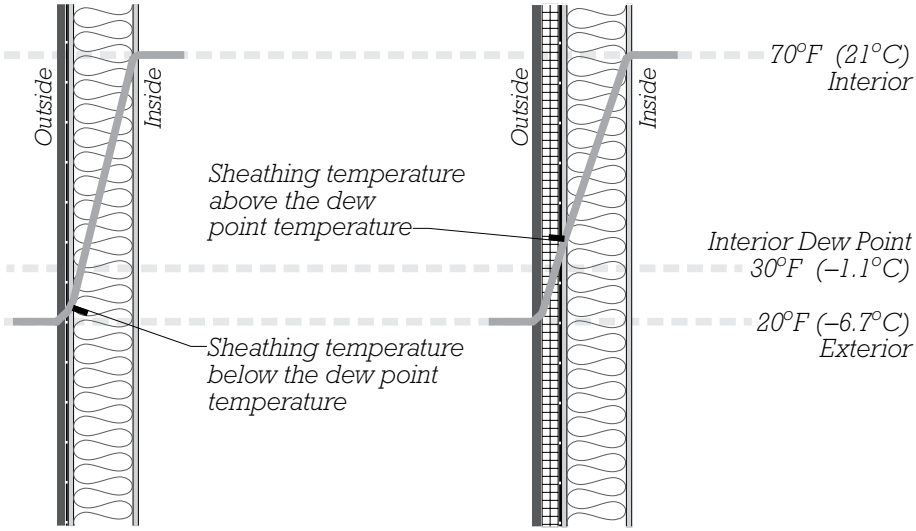


FIGURE 16.16
In a cold-climate wall assembly, the vapor retarder is located close to the interior side of the wall (directly under the wallboard in this illustration) where it limits the diffusion of water vapor from the warm interior toward the cooler, drier exterior.



(A) TEMPERATURES IN THE WALL WITHOUT EXTERIOR INSULATION

(B) TEMPERATURES IN THE WALL WITH EXTERIOR INSULATION

FIGURE 16.17
The sloped lines graph temperatures from inside to outside across each assembly. In (*A*), the exterior sheathing temperature is below the dew point temperature of the interior air, making it vulnerable to condensation. In (*B*), by adding insulation outside of the sheathing, the sheathing temperature is raised and the risk of condensation is reduced.

permeability in response to changing conditions within the assembly.

Where a fuller understanding of the behavior of an enclosure assembly is needed, computer models that simulate temperature and moisture conditions within the assembly over the course of several years' exposure to interior and exterior conditions specific to the project and its geographic location may be used to study various wall design and moisture control strategies.

Exterior Insulation and Controlling Condensation

In the wall assembly in Figure 16.17*A*, the inward facing side of the exterior sheathing can act as a *condensing surface*. Without a vapor retarder in the assembly, water vapor can readily diffuse into the assembly and the relative humidity inside the wall cavity can rise. As this increasingly moist air comes into contact with the cold back side of the wall sheathing, it can be cooled below its dew point temperature and condensation can occur.

As already discussed, one strategy for preventing such condensation is to insert a vapor retarder on the warm side of the wall, reducing the diffusion of moisture vapor into the assembly. Another way to prevent condensation at the back side of the sheathing is to raise the sheathing temperature. This is done by adding *exterior insulation*, as shown in Figure 16.17*B*. As exterior insulation is added, the sheathing effectively moves closer to the warm interior and its temperature rises. By adding sufficient insulation to bring the temperature of the sheathing above dew point conditions, condensation can be prevented, even without a vapor retarder.

Considerations of moisture condensation within an enclosure assembly relate not only to water vapor diffusion, but also to the possibility of water vapor carried by air leakage. In fact, air leakage has the potential to transport quantities of moisture vapor an order of magnitude (10 times) greater, or more, than that which occurs through vapor diffusion. That is to say, even small breaches in the air barrier system can allow the passage of large quantities of air and moisture. For these reasons, the addition of exterior insulation is an effective means to reduce condensation risks from both vapor diffusion and air leakage, and to improve the resilience and durability of any building enclosure assembly.

SEALING JOINTS IN THE EXTERIOR WALL

Joint seals, or *sealant joints*, prevent the passage of air and water through the exterior enclosure while still allowing for dimensional tolerances during assembly and movement between components once the building is completed. They are used everywhere gaps between different materials and parts must be closed. Joint seals are used, for example, between panels of a cladding

system, between glass and the frames that hold the glass, between the individual parts of window and curtain wall assemblies as well as between these assemblies and the solid walls that surround them, at the edges and seams of roofing and waterproofing membranes, at flashing joints, and more.

Joint Seal Materials

Gunnable Joint Sealants

Gunnable joint sealants are viscous, sticky liquids that are injected into the joints of a building with a *sealant gun* (Figure 16.18). They cure within the joint to become rubberlike seals that adhere to the surrounding surfaces and seal the joint against the passage of air and water.

Gunnable joint sealants can be grouped conveniently into three categories according to the amount of change in joint size that each can safely withstand after curing:

1. *Low-range sealants*, or *caulks*, have very limited *elongation* (stretching and squeezing) capabilities. They are used for filling minor cracks or nonmoving joints, especially in preparation for painting. Most caulks cure by evaporation of water or an organic solvent and shrink substantially as they do so. None are used for sealing joints in exterior wall systems. Although the term caulk is best applied only to low-range sealants, in common usage it is also sometimes used more broadly to refer to any sealant, regardless of elongation capability.
2. *Medium-range sealants*, such as butyl rubber or acrylic latex, have elongation capacity in the range of plus or minus 5 to 12 percent. Butyl sealants are highly water resistant and commonly used in roofing and sheet metal work. Acrylic latex sealants are easy to apply and find broad use in sealing many kinds of exterior nonworking (nonmoving)

Figure 16.18
Applying a high-range gunnable sealant to a joint between precast concrete curtain wall panels, using a sealant gun. The installer moves the gun slowly so that a bulge of sealant is maintained just ahead of the nozzle. This exerts enough pressure on the sealant so that it fully penetrates the joint. Following application, the wet sealant is smoothed and compressed into the joint with a convex tool, much as a mason tools the mortar joints between masonry units. *(Courtesy of Morton Thiokol, Inc., Morton Chemical Division.)*

joints where the better performance of high-range sealants is not needed. Like most low-range sealants, medium-range sealants also cure by the evaporation of water or organic solvents and undergo shrinkage as they cure.

3. *High-range sealants* can reliably sustain elongations up to as much as 100 percent, and are the appropriate choice for sealing working joints (joints that move) in exterior wall systems. Because most high-range sealants cure chemically, rather than by the evaporation of water or organic solvents, they do not shrink as they cure. They adhere tenaciously to the sides of properly prepared substrates. They are highly resilient, returning to their original size and shape after being stretched or compressed. And they are resistant to the effects of weather and sun.

Silicones account for the largest share of high-range sealants used in building construction. They reliably adhere to a broad range of substrates, are highly resistant to UV-radiation and other effects of the weather, and have an expected service life of 20 years or more. *Polyurethanes* are the next most-used type. They are physically tough, with high resistance to puncture, tearing, and abrasion. Unlike silicones, polyurethanes can be painted. However, polyurethanes are UV-sensitive and (unless painted) gradually develop a chalky surface. Their expected service life is up to 10 years. *Silane-modified hybrid sealants*, relatively new to the construction market, combine the physical toughness of polyurethanes with many of the desirable performance qualities of silicones. They have excellent curing properties and adhesion, are paintable, are lower in unhealthful emissions, have an expected service life of 20 years or more, and are less costly than silicones.

Solid Joint Materials

Solid joint materials are made in various forms and from a broad range of preformed materials. Synthetic rubber *gaskets* are frequently used for dry glazing, where they are compressed into the joint between the glass and the glazing stop, sealing tightly against both sides. Denser, and more rigid adhesive *solid tapes*, frequently made of EPDM (ethylene propylene diene monomer) or butyl rubber, are used in glazing and material joining applications. They both seal and cushion the joint, and are stiff enough to maintain a predictable spacing between the elements being joined (Figure 16.19). Compressible *foam tapes* are used for all sorts of sealing and joint-filling applications. Some come impregnated with high-range sealant. They are provided highly compressed in an

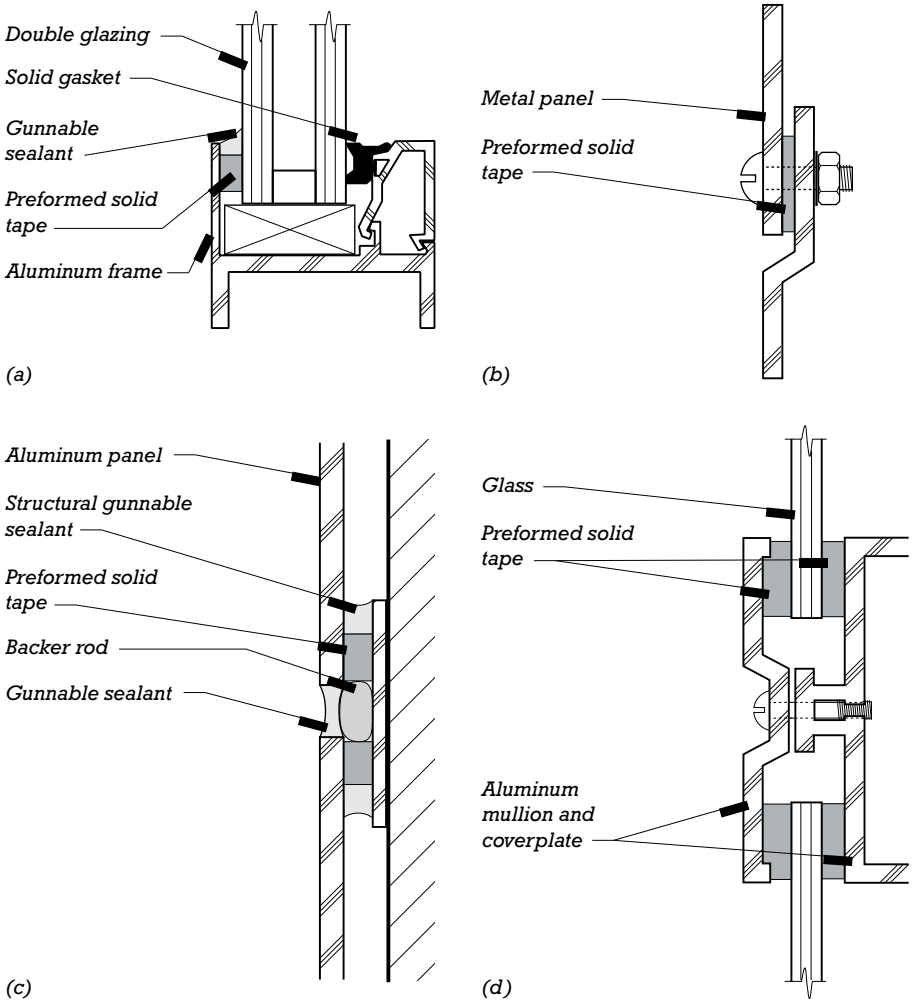


FIGURE 16.19

(*a*) Solid tape is adhered to the vertical leg of the aluminum frame. Next, the glazing is inserted and an aluminum glazing bead with a solid gasket is snapped into place, pressing the glazing tightly between the gasket and the solid tape. Lastly, gunnable sealant is installed over the solid tape for a better exterior weather seal. (*b*) A solid tape seals the nonmoving joint between two adjacent metal panels. (*c*) Solid tape holds the aluminum panels at a controlled distance from the backing plate. Structural sealant adheres the panels to the backing. (Though not shown here, the backing plate is also fastened to the wall.) A backer rod and gunnable sealant form a weather seal at the face of the panels. Backer rods are discussed in the next section of the text. (*d*) Solid tape holds sheets of single glass between an aluminum mullion and its coverplate.

airtight wrapper. When unwrapped and inserted into the joint, the tape expands to fill the joint and its sealant material cures with moisture from the air to form a permanent seal.

Installing and Sizing Sealant Joints

Before sealant is installed, the joint surfaces must be cleaned of oil, dirt, oxide, moisture, concrete form release compound, and other contaminants. Where necessary, the edges of the joint are painted with a liquid *primer* to improve adhesion between the sealant material and the joint surfaces. Next, a *backer rod* is inserted into the joint. This is a cylinder of compressible, flexible plastic foam that is a bit larger in diameter than the width of the joint. It is pushed into the joint, where it is held by friction. Placement of the backer rod controls the depth of the sealant, maintaining optimum proportions of the sealant bead and avoiding waste of sealant material. Lastly, the sealant material is extruded into the joint from the nozzle of a sealant gun and then mechanically tooled, much as a masonry mortar joint is tooled, to compress the material firmly against the sides of the joint and the backer rod. Tooling also produces a smoother surface and creates the desired surface profile. The backer rod's role is now finished but, being inaccessible, it remains in the joint (Figure 16.20).

The proper width of the sealant joint depends on the range of joint movement and the capacity of the sealant. For example, if a joint is expected to undergo up to ¼ inch (6 mm) of movement, a Class 25 sealant (capable of 25 percent elongation or compression) requires a 1-inch (25-mm) joint, whereas a Class 50 sealant (capable of 50 percent change) requires only a ½-inch (12-mm) joint.

Depth of the joint is also controlled to minimize stresses in the sealant material when it is stretched or compressed. A sealant joint should be no deeper than the width of the joint and no thinner than one-third its width. To minimize stresses in the sealant material in a moving joint, the depth of the joint at its center should be ½ the joint width. Practical sizes for gunnable sealant joints range from ¼ inch (6 mm) up to approximately 2 inches (50 mm) in width and depths from ¼ to ¾ inch (6 to 18 mm).

In any sealant joint, it is important that adhesion occur on only two sides of the joint. When sealant adheres on three sides, its movement capacity becomes restricted. Where backer rods are used, the composition of the backer rod material itself prevents sealant adhesion along the underside of the joint. However, in joints that are too shallow to fit a backer rod, a *bond breaker* tape or coating is applied to prevent three-sided adhesion (Figure 16.21).

The following chapters, in which various systems of building enclosure are discussed, include many diagrams and photographs illustrating the use of sealant joints to control the passage of water and air through the enclosure.

Interior Sealant Joints and Indoor Air Quality

When sealant joints are installed inside the building enclosure, they are a potential source of emissions of VOCs and other air pollutants. See Chapter 22 for more information about indoor air quality and low-emitting interior materials.

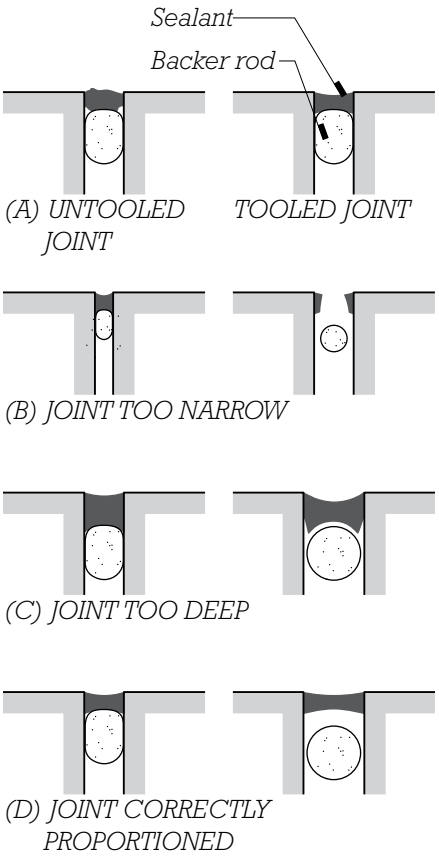


FIGURE 16.20
Good and bad examples of sealant joint design. (*A*) This properly proportioned joint is shown both untooled and tooled. The untooled sealant is unsightly, does not fill the joint uniformly, and does not fully adhere to the sides of the joint. (*B*) When a joint is too narrow, it may exceed the elongation capacity of the sealant when it opens. (*C*) If a joint is too deep, sealant is wasted, and the edges of the sealant bead are overstressed when the joint opens. (*D*) A correctly proportioned joint is wide enough so that the expected elongation does not exceed the safe range of the sealant. For most joints, optimum depth is one-half the joint width.

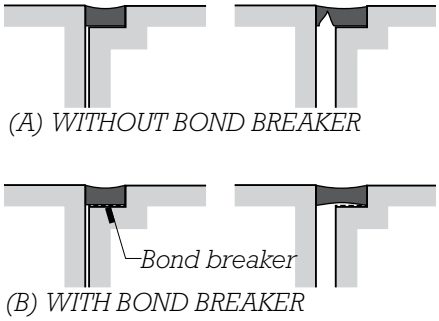


FIGURE 16.21
(*A*) When sealant adhesion occurs on three sides of a joint, the sealant loses most of its elongation and compression capacity. (*B*) Where joints are too shallow to include a backer rod, a bond breaker plastic tape or liquid coating is applied in the bottom of the joint before the sealant is installed.

MasterFormat Sections for Designing the Building Enclosure

07 21 00	**THERMAL INSULATION**
07 25 00	**WEATHER BARRIERS**
07 26 00	**VAPOR RETARDERS**
07 27 00	**AIR BARRIERS**
07 91 00	**PREFORMED JOINT SEALS**
07 91 13	Compression Seals
07 91 16	Joint Gaskets
07 91 23	Backer Rods
07 92 00	**JOINT SEALANTS**
07 92 13	Elastomeric Joint Sealants

Key Terms

building enclosure, building envelope
thermal conduction
thermal convection
Outdoor-Indoor Transmission Class (OITC)
loadbearing wall
curtain wall
barrier wall
face-sealed wall
mass wall
gravity
momentum
surface tension
capillary action
air pressure
wash
pressure-equalized design
drained cladding, rainscreen cladding
cavity wall
vented cladding
ventilated cladding
water-resistive barrier (WRB)
thermal insulation
thermal resistance, R, RSI
thermal bridge
thermal conductivity
continuous insulation
thermal radiation
radiant barrier
emissivity
stack effect
air barrier
air permeance
air barrier assembly
air barrier system
air and water-resistive barrier (AWB)
air-weather barrier
water vapor
relative humidity
condensation
dew point temperature
vapor pressure
vapor retarder
vapor permeance
perm
vapor barrier
condensing surface
exterior insulation
joint seal, sealant joint
gunnable joint sealant
sealant gun
low-range sealant, caulk
elongation
medium-range sealant
high-range sealant
silicone sealant
polyurethane sealant
siliane-modified hybrid sealant
solid joint material
gasket
solid tape
foam tape
sealant primer
backer rod
bond breaker

Review Questions

1. What are the primary functional requirements of the building enclosure? Describe one or two ways that each requirement may be satisfied in the design of the enclosure.
2. Explain the differences between an exterior loadbearing wall and a curtain wall.
3. What are the forces that can move water through an opening in an exterior wall? How can each of these forces be neutralized?
4. Give an example of thermal bridging and how it can be mitigated.
5. What are the possible harmful effects of unintended air leakage through the building enclosure?
6. Using a series of simple sketches, explain the principles of sealant joint design. List several sealant materials suitable for use in the joints that you have shown.

Exercises

1. Examine the exterior cladding of a building with which you are familiar. Look especially for features that have to do with insulation, condensation, drainage, air leakage, and movement. Sketch a detail of how this cladding is installed and how it works. You will probably have to guess at some of the hidden features, but try to produce a complete, plausible detail. Add explanatory notes to make everything clear.

2. Obtain wall and/or roof sections and details from the construction drawings of a building. Identify the materials used to control the flow of heat, air, moisture, and water vapor and trace the paths of each of these through the various sections and details.

3. Prepare a sample sealant joint, using a backer rod and silicone sealant obtained from a hardware store or building materials supplier. Apply the sealant to two parallel pieces of quarry tile or glass that are taped together with a spacer between them. After the sealant has had time to cure (a week or so), remove the tape and spacer and test the joint by pulling and twisting it to find out how elastic it is and how well the sealant has adhered to the substrate.

Selected References

Aksamija, Ajla. *Sustainable Facades: Design Methods for High-Performance Envelopes*. Hoboken, NJ, John Wiley & Sons, 2013.

ASHRAE. *ASHRAE Handbook—Fundamentals*. Atlanta, updated regularly.

This handbook provides a definitive treatment of the physics of heat and moisture transfer through building assemblies and the application of these principles to building construction methods.

Dow Corning. *Building Envelope Weatherproofing Manual*. 2012. Available online at consumer.dow.com/documents/en-us/app-tech-guide/62/62-14/62-1471-01-building-envelope-weatherproofing-manual.pdf.

An easy-to-understand yet comprehensive guide for the design of sealant joints.

Kesik, Ted J. "Managing Enclosure Heat Flows," Whole Building Design Guide (website). Washington, DC, National Institute of Building Sciences. Available online at www.wbdg.org/resources/managing-enclosure-heat-flows.

A thorough review of issues related to the control of heat flow through the building enclosure.

Klosowski, Jerome, and Andreas T. Wolf. *Sealants in Construction* (2nd ed.). Boca Raton, FL, CRC Press, 2016.

Lstiburek, Joseph. "BSI-001: The Perfect Wall," Building Science Insights, Building Science Corporation, 2010. Available online at buildingscience.com/documents/insights/bsi-001-the-perfect-wall.

A clear, readable discussion of the four major control layers in the building enclosure and their optimum configurations.

Rousseau, M. Z., G. F. Poirier, and W. C. Brown. "Pressure Equalization in Rainscreen Wall Systems," Construction Technology Update No. 17. National Research Council Canada, 1998. Available online at www.nrc-cnrc.gc.ca/ctu-sc/ctu_sc_n17.

A dated but still relevant discussion of pressure-equalized design and control of rain penetration in exterior walls.

Straub, John. *High Performance Enclosures. Westford, MA, Building* Science Press, 2012.

A comprehensive treatment of the contemporary, high-performance building enclosure.

Straub, John, and Graham Finch. "RR-0907: Ventilated Wall Claddings: Review, Field Performance, and Hygrothermal Modeling." Research Reports, Building Science Corporation, 2009. Available online at buildingscience.com/documents/reports/rr-0907-ventilated-wall-claddings-review-performance-modeling/view.

A thorough discussion of the physical behavior of drained cladding systems.

Websites

Building Science Corporation: buildingscience.com
A comprehensive source for articles pertaining to the functional requirements of the building enclosure.
RDH: www.rdh.com/research-forensics/technical-bulletins-whitepapers
Another excellent source for research and guidelines on the performance of the building enclosure.
Tremco (construction sealants): www.tremcosealants.com/category/sealants.aspx
An easy-to-explore manufacturer's website for all kinds of joint sealing materials.
Whole Building Design Guide, Building Envelope Design Guide: www.wbdg.org/guides-specifications/building-envelope-design-guide
U.S. National Institute of Building Sciences comprehensive guide to building enclosure design and construction.

17

Roofing

- **Low-Slope Roofs**
  - Roof Decks
  - Thermal Insulation
  - Air Barriers
  - Vapor Retarders

  Sustainability and Roofing

  - Membranes for Low-Slope Roofs
  - Traffic Decks
  - Roof Edge and Drainage Details
  - Structural Metal Panel Roofing
- **Steep Roofs**
  - Shingles
  - Architectural Sheet Metal Roofing

  Dissimilar Metals and Galvanic Corrosion

- **Cool Roofs**
- **Green Roofs**
- **Photovoltaic Systems**
- **Roofing and the Building Codes**

A hilltop residence in a fire-prone area of southern California is roofed with noncombustible corrugated steel. The simple roof form is elevated above the main living space of the house, providing shade from the sun and allowing cool offshore breezes to circulate freely around and through it. *(Photo by Tim Bies, courtesy of Olson Sundberg Kundig Allen Architects.)*

A building's roof is its first line of defense against the weather, protecting it from rain, snow, and sun. The roof helps to insulate the building from extremes of heat and cold and to control the accompanying problems of air leakage and water vapor condensation. And like any frontline defender, it must itself take the brunt of the attack: A roof is subject to the most intense solar radiation of any part of a building. At midday, the sun broils a roof with radiated heat and ultraviolet light. On clear nights, a roof radiates heat to the blackness of space and becomes colder than the surrounding air. Between noon and midnight of the same day, it is possible for the surface temperature of a roof to vary from near boiling to below freezing. In cold climates, snow and ice cover a roof after winter storms, and cycles of freezing and thawing gnaw at the materials of the roof. A roof is vital to the sheltering function of a building, while singularly vulnerable to the destructive forces of nature.

Roofs can be covered with many different materials. These can be organized conveniently into two groups: those that work on steep roofs and those that work on low-slope roofs, or roofs that are nearly flat. The distinction is important: A steep roof drains itself quickly of water, giving wind and gravity little opportunity to push or pull water through the roofing material. Therefore, steep roofs can be covered with materials that are fabricated and applied in small, overlapping units—shingles of wood, slate, or artificial composition; tiles of fired clay or concrete; or even tightly wrapped bundles of reeds, leaves, or grasses. There are several advantages to these materials: Many of them are inexpensive. The small, individual units are easy to handle and install. Repair of damage to the roof is easy. The effects of thermal expansion and contraction, and of movements in the structure that supports the roof, are minimized by the ability of the small roofing units to move with respect to one another. Water vapor vents itself easily from the interior of the building through the loose joints in the roofing material. In addition, a steep roof of well-chosen materials skillfully installed can be a delight to the eye.

Low-slope roofs have none of these advantages. Water drains relatively slowly from the surfaces, and small errors in design or construction can cause them to trap puddles of standing water. The membranes that cover low-slope roofs must be absolutely watertight. Even small punctures, tears, or gaps in seams, caused by defects in construction, physical wear and tear, or movements within the building structure, can allow water to enter the building structure and its interior, with potentially disastrous results. Or, water vapor pressure from within the building can blister and rupture the membrane. But low-slope roofs also have overriding advantages: A low-slope roof can cover a building of any horizontal dimension, whereas a steep roof becomes uneconomically tall when used on a very broad building. A building with a low-slope roof has a much simpler geometry that is often less expensive to construct. Low-slope roofs, when appropriately detailed, can also serve as balconies, decks, patios, and even landscaped gardens or parks.

FIGURE 17.1
A steep roof can be made waterproof with any of a variety of materials. This thatched roof is being constructed by fastening bundles of reeds to the roof structure in overlapping layers in such a way that only the butts of the reeds are left exposed to the weather. *(Courtesy of Warwick Cottage Enterprises.)*

FIGURE 17.2
The finished thatched roof has gently rounded contours and a pleasing surface texture. The decorative pattern of the ridge cap is the unique signature of the thatcher who made the roof. *(Courtesy of Warwick Cottage Enterprises.)*

Low-Slope Roofs

The *slope*, or *pitch*, of a roof surface is described numerically as a vertical dimension, or *rise*, occurring over some horizontal distance, or *run*. In the United States, roof slopes are always expressed over a run of 1 foot (12 inches), such as ¼:12, 3:12, 6:12, etc. In Canada, roof slopes are expressed always with a rise of 1, so that, for example, a ¼:12 pitch is described as 1 in 48, a 3:12 pitch is 1 in 4, and a 6:12 pitch is 1 in 2.

Roofs that are close to horizontal in pitch, that is, with slopes less than 3:12 to 2:12 (1 in 4 to 1in 6), are referred to as *low-slope roofs* (or often, inaccurately, as "flat roofs").

They are made up of multiple, interactive parts: The *roof deck* is the structural surface that supports the roof. *Thermal insulation* is installed to slow the passage of heat into and out of the building. An *air barrier* restricts the leakage of air through the roof assembly, and a *vapor retarder*, used in colder climates or when enclosing humid spaces, prevents moisture vapor from condensing within it. The *roof membrane* is the impervious sheet of material that keeps water out of the building. Additional layers within the assembly may increase resistance to fire, protect soft insulation boards from damage by foot traffic, or separate replacement roof materials from older, previously installed materials. *Drainage components*, such as roof drains, gutters, and downspouts, remove the water that runs off the membrane. Around the membrane's edges and wherever it is penetrated by pipes, vents, expansion joints, or roof hatches, special *flashings* and details are designed and installed to prevent water penetration.

Roof Decks

Previous chapters of this book have presented the types of structural decks ordinarily used under low-slope roofs: plywood or OSB wood panels over wood joists, solid wood decking over heavy timber framing, mass timber panels, corrugated steel decking, panels of wood fiber bonded together with portland cement, sitecast concrete slab, and precast concrete slab. The structural deck and its supporting members must be strong and stiff enough to support rain and snow loads, as well as be resistant to the forces of wind uplift. The deck itself, or the insulation materials on top of it, must slope toward drainage points for water on top of the roof membrane to drain efficiently and reliably.

A slope of at least ¼ inch per foot of run (1 in 48) is normally required by the building code and most manufacturers of low-slope roof membranes. To achieve this, the beams

that support the roof deck may be sloped by varying the height of their supporting columns, or the supporting structure may be constructed level and slope created by a layer of thermal insulation of varying thickness installed on the top of the deck.

If a low-slope roof does not drain efficiently, *ponding* can occur, in which areas of water remain standing for extended periods of time. Except with roof membranes specially designed to tolerate standing water, this can cause deterioration of the membrane and increase the chance of leakage. With longer-span roof structures, water accumulation in low spots caused by structural deflections is also a concern. As puddles deepen and increase in weight, the structure may deflect further, progressively attracting more and more water and becoming heavier and heavier. If water cannot drain from these areas and continues to accumulate, overloading and even structural collapse is a possibility.

The roof membrane must be laid over a smooth, continuous surface. A wood deck should have no large gaps, knotholes, or protruding fasteners, or it may be covered with another material to provide a smoother surface. A sitecast concrete deck should be troweled smooth, and a precast concrete plank deck, if not topped with a concrete fill, must be grouted at junctions between planks to fill the gaps. A corrugated steel deck is covered to create a continuous flat surface. This is done with rigid insulation boards or some variety of *substrate board*, thin panels of wood fiber or gypsum that are attached to the top surface of the metal deck. Gypsum panel substrate boards are also installed over wood and metal roof decks to increase the fire resistance of the roof assembly.

It is important that the roof deck be dry at the time roofing operations commence to avoid later problems with water trapped under the roof membrane. A deck should not be roofed when rain, snow, or frost is present in or on the deck material. Concrete decks and insulating fills must be cured and adequately dried.

If a deck is large in extent, the roofing system should be provided with enough movement joints to keep expansion and contraction within the deck from stressing the roof membrane. Where building separation joints occur within a building structure, these joints must carry through the roof membrane system as well (Figure 17.21). Where such joints do not occur or are too far apart to satisfy the requirements of the membrane, *area dividers*, which are much like building separation joints but do not extend below the surface of the roof deck, may be installed (Figure 17.22).

Thermal Insulation

Insulation Locations for Low-Slope Roofs

Figure 17.3 illustrates options for locating thermal insulation within a low-slope roof assembly.

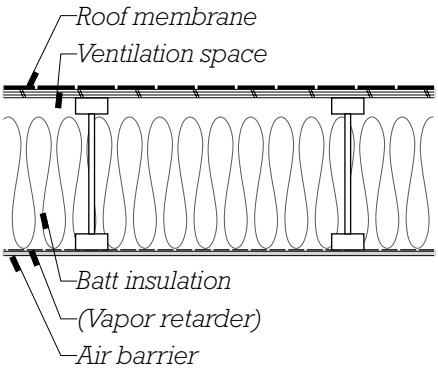
Below the roof deck, mineral or glass fiber batts may be installed between framing members (Figure 17.3*A*). Because these insulation types are permeable to the flow of air, an airspace, ventilated to the exterior, is usually required above the insulation. This space allows for the dissipation of water vapor that may infiltrate from the interior below and prevents excessive condensation on the underside of the deck. Batt insulation is economical and generally trouble free. But this arrangement leaves the roof deck and upper portions of the supporting structure exposed to exterior temperature and humidity fluctuations. And it requires special detailing so that the air spaces in each framing bay can be ventilated to the exterior.

Alternatively, if the space under the roof deck is insulated with air-impermeable rigid or spray foam insulation, no ventilation is required and the insulation is installed tight to the underside of the deck (Figure 17.3*B*). Without exterior vents, detailing at the roof edges is simplified. Spray foam can also serve as the air barrier, and if needed, vapor retarder, in the assembly. But this insulation type is more expensive than batts. And if excess moisture finds its way between the insulation and the deck, it can become trapped there with no easy way to escape.

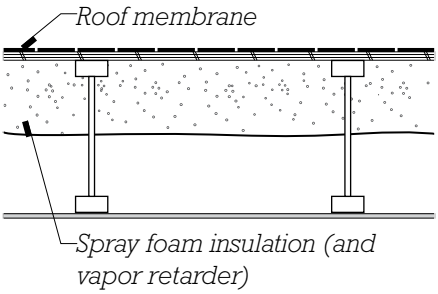
The most common location for low-slope roof insulation is above the roof deck, beneath the roof membrane (Figure 17.3*C*)—a configuration also called a *compact insulated roof*. Insulation boards of various material types that are dense enough to support the roof membrane and withstand occasional foot traffic are used. In this configuration, the roof deck and supporting structure are protected from exterior temperatures. The insulation is protected from the weather by the roof membrane, and the roof membrane itself remains exposed to the exterior environment.

In a *protected membrane roof* (*PMR*), insulation is installed above the roof membrane (Figure 17.3*D*). In this configuration, the membrane is protected from extremes of heat and cold and is located on the warm side of the insulation. Insulation types, such as extruded polystyrene, that can withstand prolonged exposure to moisture without deterioration are used. The insulation boards are usually held in place with a layer of *ballast*, consisting of stone aggregate or concrete pavers (Figures 17.4 and 17.17). Because the roof membrane is shielded from sunlight and temperature extremes, its life span can be as much as doubled compared to one remaining exposed

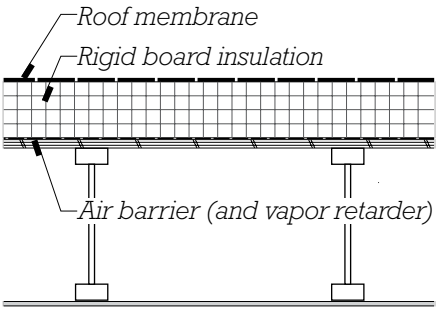
FIGURE 17.3
Insulation locations within low-slope roof assemblies. Typical locations for air barriers and vapor retarders (when required) are also shown. Roof slope is not shown, and other possible components, such as insulation coverboards or materials to improve fire resistance, have been omitted for simplicity. While wood construction is shown here, the same strategies apply to insulating steel and concrete roof deck systems as well.



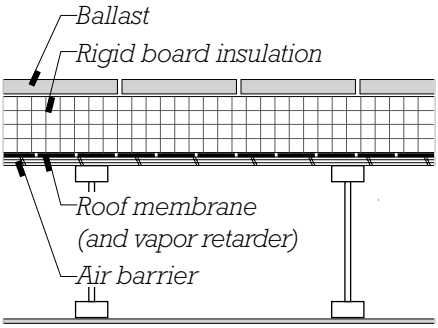
(A) AIR-PERMEABLE INSULATION BENEATH THE ROOF DECK



(B) AIR-IMPERMEABLE INSULATION BENEATH THE ROOF DECK



(C) INSULATION ABOVE THE ROOF DECK



(D) INSULATION ABOVE THE ROOF MEMBRANE

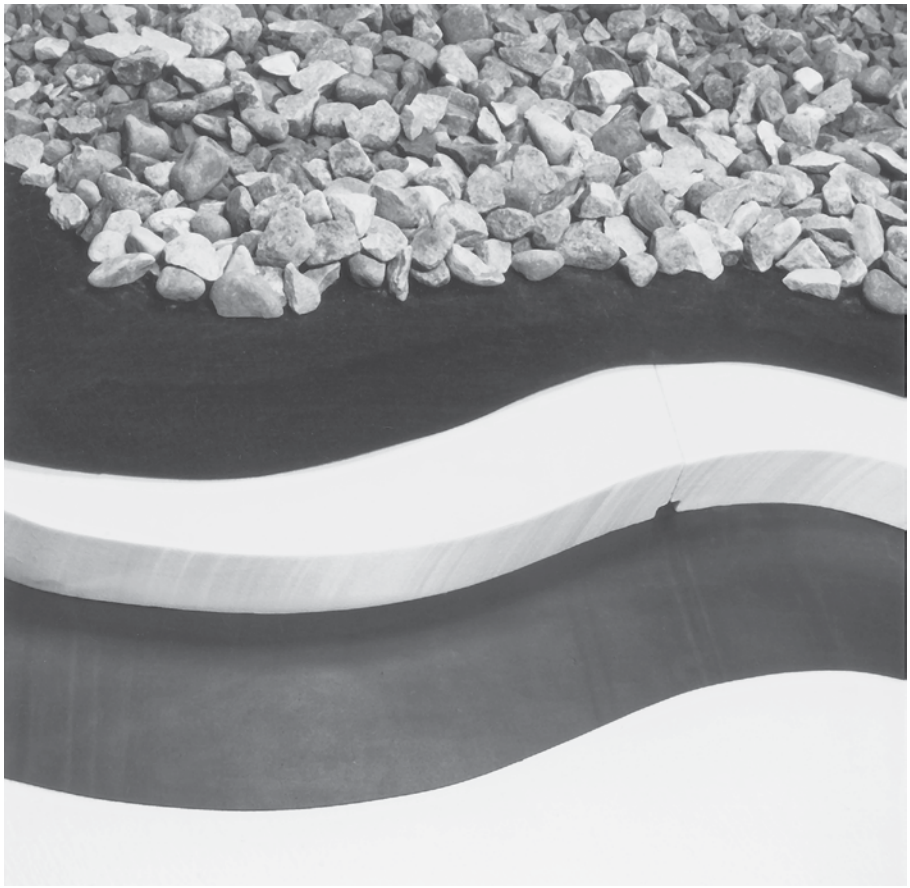


FIGURE 17.4
A cutaway detail of a protected membrane roof shows, from bottom to top, the roof deck, membrane, extruded polystyrene foam insulation, a polymeric fabric that separates the ballast from the insulation, and ballast. To resist the scouring action of the wind, loose stone aggregate ballast ranges in size from 1½ to 2½ inches (38 to 64 mm) in diameter. *(Photo provided by the Dow Chemical Company.)*

to the elements. However, the exposed roof insulation may be susceptible to moisture absorption and partial loss of insulation value. And repairs to protected membrane roofs are more difficult because accessing the membrane requires removal of the layers of material above it.

Rigid Insulating Materials for Low-Slope Roofs

When placed above the roof deck, insulating materials must not only have good thermal resistance. They must also resist the weight of materials above; loads imposed by wind, rain, and snow; and the pressures of foot traffic. If part of a hot-applied system, they must not melt when exposed to hot asphalt or catch fire when exposed to open flame. And if part of a protected membrane roof, they must be resistant to moisture.

No single material has all these virtues and the best choice is often a combination of materials, or a composite that combines two or more materials into one product, exploiting the best qualities of each. For example, insulation under a built-up roof membrane might include a bottom layer of polyisocyanurate foam with high insulating value and a top layer of perlite board resistant to the hot asphalt used in assembling the membrane plies. Examples of rigid insulating materials for low-slope roof applications are described in Figure 17.5.

Insulation Type	Composition	R-Value[a]	Advantages	Disadvantages
Cellulose fiberboard	Wood or vegetable fibers and binder	2.8 *19*	Compatible with hot bitumens	Low thermal resistance, susceptible to moisture absorption
Perlite board	Expanded volcanic glass granules and binder	2.8 *19*	Inert, fire-resistant, compatible with hot bitumens, dimensionally stable	Low thermal resistance
Cellular glass board	Heat-fused, closed-glass ceils with kraft paper facers	2.9 *20*	Inert, fire-resistant, compatible with hot bitumens, dimensionally stable	Low thermal resistance
Mineral fiberboard	Molten rock or blast furnace slag fibers	4 *28*	Inert, fire-resistant, compatible with hot bitumens, dimensionally stable	
Expanded and extruded polystyrene foam	Closed-cell plastic foam	3.2–5.0 *22–35*	Moisture-resistant	Combustible, expands and contracts with temperature changes
Polyisocyanurate foam	Closed-cell plastic foam with facings of aluminum foil, or glass fiber or cellulosic mats	5.6 *39*	High thermal resistance, moderate resistance to hot bitumens	Expensive, thermal resistance may decrease over time or at low temperatures
Lightweight insulating concrete	Concrete with lightweight aggregate or foaming agents	1–1.5 *6.9–10*	Inert, easily tapered for slope, fire-resistant, dimensionally stable	Residual moisture may cause blistering of the roof membrane
Vacuum-insulated board	Vacuum-sealed fiberglass foam	50 *300*	High thermal resistance in very thin profile	Very high cost

[a]R-values are per unit of thickness, expressed first in inch-pound units of ft^2-hr-°F/BTU-in. and second in metric units (italicized) of m^2-°K/W-m. For example, for an insulation material with R-value of 5 ft^2-hr-°F/BTU-in. (35 m^2-°K/W-m), 3 inches (76 mm) of the material would have a total insulation value of 5 ft^2-hr-°F/BTU-in. × 3 in. = R-15 or 35 m^2-°K/W-m × 0.076 m = RSI-2.7.

FIGURE 17.5
Rigid insulating materials for low-slope roofs.

An *insulation coverboard*, made of materials similar to those described for substrate boards, may be placed over rigid insulation prior to installation of the roof membrane. The coverboard provides a more stable surface for the roof membrane, protects against damage from foot traffic, and increases the fire resistance of the roof assembly.

Lightweight insulating concrete is an economical insulating material that also creates a nailable roof deck. Made with lightweight aggregates or foaming air-entraining agents, this material has densities ranging from 20 to 40 pounds per cubic foot (320 to 640 kg/m^3), compared to 145 pounds per cubic foot (2320 kg/m^3) for conventional concrete. Lightweight concrete may be applied over corrugated steel decking or a structural concrete deck and can be easily tapered during installation to create slope. Its thermal resistance is relatively low. However, plastic foam boards may be embedded within it to achieve higher insulating values. Lightweight concrete contains large amounts of free water at the time it is placed. It must be cured and thoroughly dried before being covered by the roof membrane. Some form of venting to allow the escape of moisture vapor from the concrete during the life of the roof is also usually advisable, via either venting of the membrane above the concrete or the use of slotted *vented metal decking* below it.

Air Barriers

As illustrated in Figure 17.3, an air barrier can be located anywhere within a roof assembly where a suitably airtight and continuous separation between the interior and the exterior can be established. At the interior, a finished gypsum board ceiling can serve this purpose (*A*). Beneath the roof deck, air-impermeable insulation may be used (*B*). When insulation is placed above the roof deck, various air-impermeable membranes may be adhered to the top side of the roof deck, below the insulation (*C*). Even structural wood panel sheathing, with attention to air sealing of gaps between panels and at fastener penetrations, can be made sufficiently airtight for this purpose (*D*).

Other alternatives (not illustrated) are also possible: A structural concrete slab roof deck can readily perform as an air barrier. Corrugated steel decking alone leaks air too easily where steel sheets overlap—but with the addition of a concrete topping, the deck can become an effective air barrier. Or, a substrate board can be applied over a corrugated metal deck, providing a flat surface onto which an air barrier membrane can be applied (Figure 17.8). The roof membrane itself can also sometimes perform as the air barrier. For best results, the membrane should be fully adhered to the underlying surface. This provides stiffness and minimizes opportunities for air to flow easily toward gaps or other discontinuities in the membrane.

Regardless of the type and location of the roof system air barrier, it must maintain a continuous airtight separation between the interior and exterior of the building. Seams and penetrations must be sealed. And, at its edges, it must integrate with the wall system air barrier. Figure 17.8 illustrates one such example.

Vapor Retarders

Like any other enclosure assembly, the need for a vapor retarder in a low-slope roof increases in a colder climate and with higher-humidity interior conditions. However, a complication is the presence of an additional vapor-impermeable layer, the roof membrane itself, in the assembly. In all but protected membrane roofs, the installation of a vapor retarder on the warm side of the insulation introduces the possibility of trapping moisture between the two impermeable layers. This makes the decision of whether to include a vapor retarder in a low-slope roof more dependent on the case-by-case analysis of the particular roofing system design.

Figure 17.3 illustrates common locations for vapor retarders in low-slope roofs. With batt insulation below the roof deck, a plastic or other vapor-retarding sheet material may be installed below the insulation batts (*A*),

Figure 17.6
Workers bedding rigid insulation boards in strips of hot asphalt over a corrugated metal roof deck. *(Courtesy of GAF Corporation.)*

Figure 17.7
Screws and large sheet metal washers secure insulation to a metal deck. *(Courtesy of GAF Corporation.)*

Sustainability and Roofing

Roofs can capture rainwater and snowmelt and conduct them to a cistern, tank, or pond for use as domestic water, industrial water, or irrigation. A properly proportioned overhang can shade south-facing windows from the high summer sun but admit warming light from the low winter sun.

A light-colored roof covering, if kept clean, can reflect half or more of the solar radiation striking its surface, improving occupant comfort and reducing the heating load on the building interior. Even darker-hued roof materials, when coated with specially formulated cool color pigments, can reflect 25 percent or more of solar radiation. Cool roofs can reduce cooling energy costs for buildings and extend the life of the roofing materials. They also reduce the absorption of solar heat and reduce the elevation of air temperatures in densely built areas, thereby reducing a building's indirect contributions to smog, degraded air quality, environmental discomfort, and other heat island effects.

A roof surface can support solar thermal collectors used to reduce building heating costs or arrays of photovoltaic modules to provide electrical power. Electrical power for building use can also be produced from thin-film photovoltaic materials laminated directly onto a variety of conventional roof coverings.

Green roofs extend the life of the roof covering materials, moderate temperature swings in the roof assembly, lessen the intensity of stormwater runoff from the roof, provide natural habitat, and create occupiable roofscapes.

Roof membranes coated with photocatalytic materials can convert various air pollutants into harmless organic materials in the presence of sunlight. Rain then washes the resulting organic material off the roof.

Energy Performance

Thermal insulating materials in roofs and walls may be the most cost-effective, planet-saving materials used in buildings. They increase occupant comfort by moderating the radiant temperatures of interior surfaces. They reduce heating and cooling energy requirements to a fraction of what they would otherwise be. They pay for themselves through energy savings in a very short period of time. The sustainability of insulation materials used in building is discussed in more detail in Chapter 7.

Low-Slope Roofs

Building and Material Life-Cycle Impacts

- Materials from demolition of built-up roof membranes are generally incinerated or taken to landfills.
- Thermoplastic single-ply membranes can be recycled into new membrane material, resilient flooring, and other accessory building products.
- Thermosetting membranes cannot be recycled.
- The NSF/ANSI 347 standard certifies single-ply roof membranes based on life-cycle, product design, manufacturing, membrane durability, and innovation criteria.
- A PVC roof membrane manufacturer EPD reports the following cradle-to-gate impacts per square meter (11 sq. ft.) of 60-mil (1.5 mm) thick membrane:

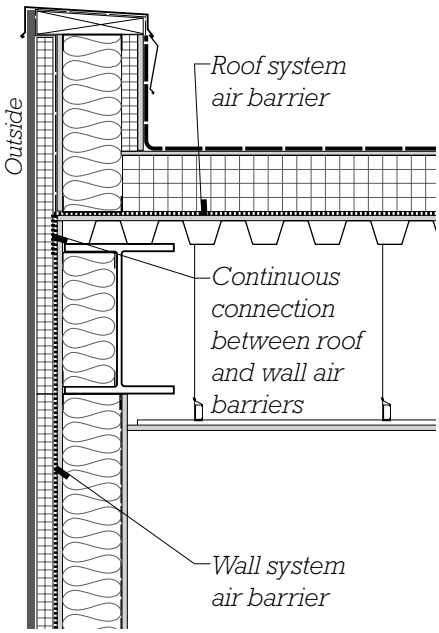


Figure 17.8
In any building, the roof and wall air barriers must meet to complete the airtight boundary between the interior and the exterior. In this example, the roof air barrier is installed over a substrate board over corrugated metal decking. The decking and substrate board extend under the parapet framing so a continuous connection can be made between the roof and wall air barriers. If a vapor retarder is required in this roof system, an air barrier membrane material can be chosen that has a low vapor permeability. On the other hand, the wall air barrier is closer to the cold exterior side of the wall and more likely to be a material that is vapor-permeable.

batts with vapor-retarding paper or foil facing may be used, or a vapor-retarding paint primer may be applied to the gypsum board ceiling. Spray foam insulation, of the higher-density closed-cell type, can also act as a vapor retarder (*B*). (Low-density, open-cell foams are vapor-permeable.) With insulation above the roof deck, a vapor retarder membrane can be installed directly over the roof deck (*C*). Traditionally, roofing felts bedded in hot asphalt were used for this application; today, manufactured self-adhered sheets are also common. In this configuration, the vapor retarder commonly performs as an air barrier as well. In a protected membrane roof, the roof membrane

Nonrenewable primary energy consumption	160 MJ (150,000 BTU)
Global warming potential	7.6 kg (17 lb) CO_2 eq.
Fresh water consumption	52 L (14 gal)

Material and Production Attributes

- Bituminous roofing is largely based on asphaltic compounds derived from coal and petroleum.
- Most roofing felts today are made with cellulose or glass fibers. Roofing felts in older buildings being demolished or reroofed may contain asbestos, a carcinogen.
- The various rubber and plastic formulations used in single-ply membranes utilize petroleum as a primary ingredient.
- NSF/ANSI 347 evaluates single-ply roofing membranes for transparent materials disclosure and the presence of hazardous material ingredients.
- For more about plastics and sustainability, see Chapter 19, "Plastics in Building Construction."

Unhealthful Materials and Emissions

- Roofing operations with hot bituminous materials emit plentiful quantities of volatile organic compounds and other chemicals that are unpleasant and potentially unhealthful.
- Adhesive bonding, solvent welding, and heat welding of single-ply membrane materials may entail release into the air of unhealthful compounds.
- Processes related to the manufacture and disposal of polyvinyl chloride (PVC) are associated with a variety of negative health effects. PVC is on the Living Building Challenge Red List and also included in Cradle to Cradle's list of banned material ingredients.

Responsible Industry Practices

- NSF/ANSI 347 evaluates single-ply roofing membrane manufacturer corporate governance and innovation.

Steep Roofs

Building and Material Life-Cycle Impacts

- Metal roofing materials can be recycled.
- Asphalt shingles can be recycled, mainly for use in asphalt paving products. Some shingles are made almost entirely of recycled tires or other recycled materials.

Material and Production Attributes

- Asphalt shingles consist mostly of petroleum.
- Metal roofing products generally have high recycled content due to the high value of these materials and the ease with which they can be recycled.
- The environmental impact of wood shingles is much the same as that of other wood products; see Chapter 3.
- Slates are quarried stone, and concrete tiles are, of course, concrete, the sustainability of which are discussed in Chapters 9 and 13, respectively.

Responsible Industry Practices

- Wood shingles and shakes can be FSC certified (see Chapter 3).

itself is positioned on the warm side of the insulation and can serve as the vapor retarder (*D*).

Membranes for Low-Slope Roofs

Membranes for low-slope roofing can have life expectancies ranging from 15 to 30 years, depending on the material and thickness, the degree of exposure to extremes of temperature and ultraviolet radiation, and the quality of the roof's installation and maintenance. These membranes fall into three broad categories: multi-ply bituminous, single-ply, and fluid-applied.

Multi-Ply Bituminous Roof Membranes

Multi-ply bituminous roof membranes are of two types, built-up or modified bitumen. A *built-up roof (BUR) membrane* is assembled in place from multiple layers of asphalt-impregnated roofing felt bedded in layers of hot bitumen (Figures 17.9 and 17.10). The felt, made from cellulose, glass, or synthetic fibers, is saturated with asphalt at the factory and delivered to the site in rolls. The hot bitumen applied in the field is usually asphalt derived from the distillation of petroleum. But for dead-level or very low-slope roofs, coal tar pitch may be used because of its greater resistance to standing water. Polymer-modified asphalts, as described later for modified bitumen roofs, may also be used. The felts are laminated in overlapping layers (plies), with the hot bitumen welding them into a unified membrane, two to four plies thick. The more plies used, the more durable the roof.

To protect the membrane from sunlight and physical wear, a layer

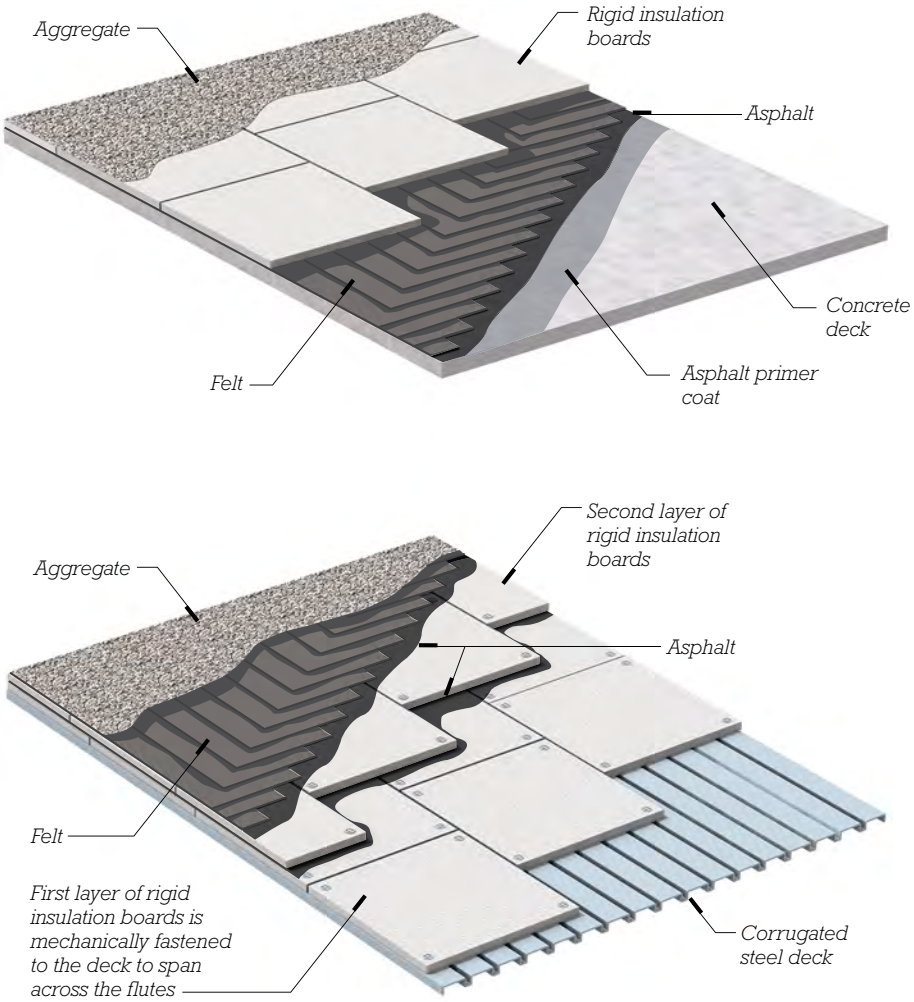


FIGURE 17.9
Two built-up roof constructions, as seen from above. The top diagram is a cutaway view of a protected membrane roof over a sitecast concrete roof deck. The membrane is made from plies of felt overlapped in such a way that no location is less than four plies thick. Rigid foam insulation boards are bedded in hot asphalt over the membrane and ballasted with stone aggregate to keep them in place and protect them from sunlight. The bottom diagram shows rigid insulation boards attached to a corrugated steel roof deck in two staggered layers to provide a firm, smooth base for application of the membrane. A three-ply membrane is shown. In cold climates, a vapor retarder may be installed between the layers of insulation or under the insulation and over a substrate board fastened to the steel deck.

FIGURE 17.10
Overlapping layers of roofing felt are hot-mopped with asphalt to create a four-ply membrane. *(Courtesy of Manville Corporation.)*

of crushed stone or mineral granules is embedded in the top surface. Less commonly, a built-up roof may be made from felt plies bedded in *cold-applied mastics*. These are asphalt compounds applied by spray or brush at ambient temperatures and then cured through solvent evaporation.

A *modified bitumen roof membrane* is made from factory-manufactured sheets of polymer-modified bitumens. Modified bitumens are asphalt materials to which compounds such as *atactic polypropylene* (*APP*) or *styrene-butadiene-styrene* (*SBS*) have been added to increase the material's flexibility, cohesion, toughness, and resistance to flow. Modified bitumen roof membrane sheets are also reinforced with plastic or glass fibers or fibrous mats. Sheet thickness typically ranges from 0.040 to 0.160 inch (1.0 to 4.0 mm).

Like a built-up roof, modified bitumen sheets are assembled in place in overlapping layers to form a multi-ply system, usually two or three plies thick. The sheets are bonded to one another in a number of possible ways: With a *torch-applied* membrane, as a roofing sheet is unrolled, an open-flame apparatus is used to thermally

fuse the underside of the sheet to the top surface of the substrate or underlying sheet. A *hot-mopped* membrane relies on the application of hot asphalt to bond the sheets, a *cold process* (or *cold-applied*) *adhesive* membrane uses liquid adhesives, and a *self-adhered* membrane relies on factory-applied adhesives (Figure 17.11).

The top ply, called the *cap sheet*, in a modified bitumen roof is surfaced with mineral granules, thin metallic laminates, or asphaltic or elastomeric coatings to provide resistance to ultraviolet deterioration, wear, and fire (Figure 17.12). Cap sheets with reflective white coatings that comply

FIGURE 17.11
Roofers bond a polymer-modified bitumen membrane to a concrete deck with a cold-applied adhesive. The seams will be heat-fused together. *(Courtesy of Koppers Company, Inc.)*

FIGURE 17.12
A roofer heat-fuses an aluminum-faced modified bitumen cap sheet to the underlying base sheet. The aluminum facing protects the membrane from the sun and reflects solar heat. *(Courtesy of Koppers Company, Inc.)*

with cool roof standards are also available. In comparison to built-up roofs, modified bitumen roofs combine the toughness and redundancy of multi-ply field application with the improved material qualities of factory-manufactured sheets. Built-up and modified bitumen systems may also be combined, with a modified bitumen cap sheet applied over several plies of built-up roofing to create a *hybrid membrane bituminous roof.* Multi-ply bituminous roofing systems account for approximately 20 percent of the North American market for low-slope roofing membranes, with the larger portion of this share belonging to modified bitumen systems.

Single-Ply Roof Membranes

Single-ply roof membranes are a diverse group of sheet materials that are applied to the roof in a single layer (Figure 17.13). Compared to multi-ply systems, they require less on-site labor, and especially in comparison to BUR membranes, they are more elastic and less prone to cracking or tearing as they age. However, single-ply membranes lack the redundancy of multi-ply membranes, making them potentially more vulnerable to leakage through small defects or gaps in seams. Common membrane thicknesses vary from 0.035 to 0.120 inch (0.9 to 3.0 mm), depending on the membrane material and the requirements of the roofing application. The membrane sheets come in rolls in standard widths ranging from 3 to 20 feet (0.9 to 6 m). They are affixed to the roof deck by adhesives, the weight of ballast, or fasteners concealed in the seams between sheets (Figure 17.14).

The materials used for single-ply membranes fall into two groups: thermoplastic and thermosetting. *Thermoplastic materials* can be softened by the application of heat and may be joined at the seams by heat (or solvent) welding. This welding process, which fuses one sheet to another, results in seams between sheets that are virtually as strong and permanent as the sheets themselves (Figures 17.15 and 17.16). *Thermosetting materials* have a more tightly linked molecular structure and cannot be softened by heat. Thermosetting sheets are joined at the seams by liquid adhesives or pressure-sensitive tapes.

Figure 17.13
Workers unfold a wide single-ply, EPDM roof membrane sheet. Using wider sheets when roofing larger areas reduces the amount of field seaming work required. *(Courtesy of Carlisle SynTec Systems.)*

The most commonly used thermoplastic roof membrane materials are *polyvinyl chloride* (*PVC*) and *thermoplastic polyolefin* (*TPO*). PVC roof membranes, made of PVC resins, plasticizers, stabilizers, and reinforcing fibers or fabrics, have a track record of successful performance established over many decades. However, concerns over negative health impacts associated with the manufacture and formulation of PVC have led to questions regarding the appropriateness of PVC for use in buildings. Although PVC manufacturers continue to improve their manufacturing processes and institute materials recycling programs in response to such concerns, segments of the construction industry have moved toward avoidance of this material in building products (for example,

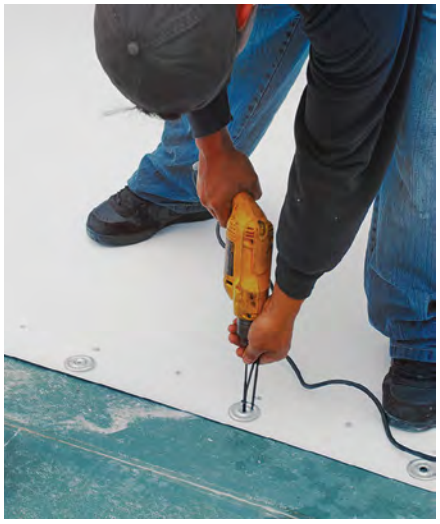


Figure 17.14
A thermoplastic membrane is attached with closely spaced fasteners along its edge. The screws are long enough to reach the wooden deck beneath the insulation layers. Oversized washers keep the membrane from tearing when subjected to wind uplift forces. *(Photo by Joseph Iano.)*

FIGURE 17.15
After the first sheet of membrane is fastened in place, the next sheet is unrolled alongside so that it overlaps the edge fasteners in the first sheet. After the seam is welded, water running on the surface of the membrane cannot reach the fastener penetrations. The surface under the roofing membrane is a gypsum insulation coverboard. *(Photo by Joseph Iano.)*

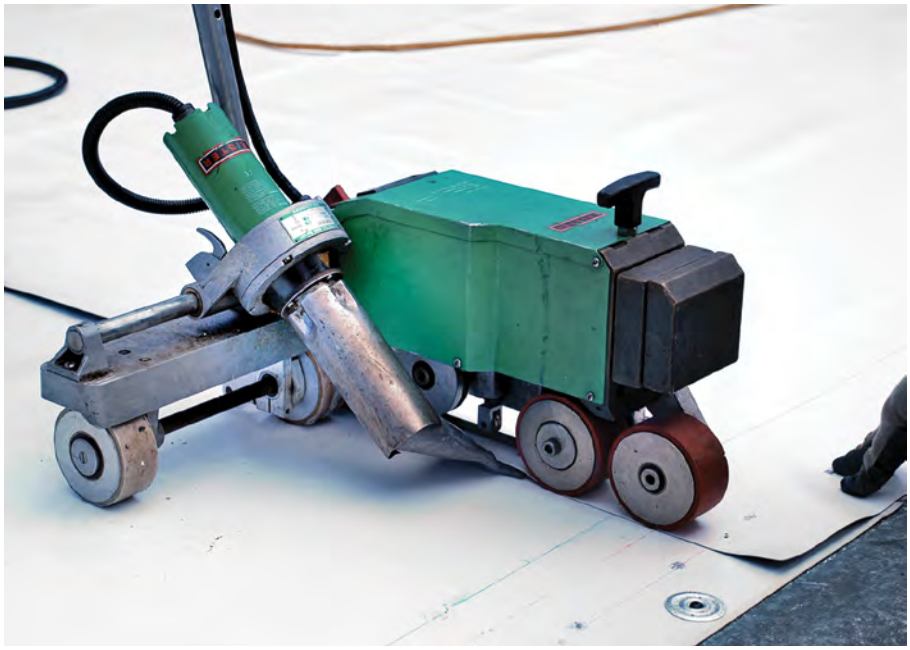


FIGURE 17.16
A hot-air welder used to weld the seams in a thermoplastic membrane. The machine delivers air at the proper temperature and travels along the seam at the prescribed rate to maintain the quality of the weld. *(Photo by Joseph Iano.)*

PVC is a Living Building Challenge Red List material). TPO roof membranes are newer to the North American roofing market. They are made from blends of polyethylene, polypropylene, and ethylene-propylene rubber polymers reinforced with fibers or fabrics. TPO membranes exhibit good resistance to heat and ultraviolet radiation, characteristics more commonly associated with thermosetting membranes, but as thermoplastics, their seams can be heat welded. Other thermoplastic roof membrane materials include *ketone ethylene ester* (*KEE*) and a class of materials referred to as PVC alloys or PVC compounded thermoplastics, made from various blends of PVC and other polymers. Thermoplastic roof membranes are generally available in a broad range of colors, including reflective white for cool roofs.

The most prevalent thermosetting roof membrane material is *ethylene propylene diene monomer* (*EPDM*), a synthetic rubber that may or may not include fiber or fabric reinforcing. EPDM has a stable chemical structure with excellent resistance to ozone, heat, ultraviolet radiation, and weathering. It is most commonly black, but is also available with a cool white surface coating. Because EPDM (like all thermoset materials) cannot be heat welded, seaming is performed with tapes or adhesives. Like PVC, EPDM has a many-decades-long track record of successful performance. Other thermosetting roof membrane materials include chlorosulfonated polyethylene (CSPE) and polyisobutylene

(PIB). Single-ply membranes account for roughly 75 percent of the North American low-slope roofing market.

Fluid-Applied Roof Membranes

Fluid-applied roof membranes are frequently used for domes, shells, and other complex shapes that are difficult to roof by other means. Such shapes are often too flat on top for shingles but too steep on the sides for built-up roof membranes; or, if doubly curved, they are difficult to cover with preformed sheets. Fluid-applied membranes are installed with a roller or spray gun, usually in several coats, and cure to form a solid membrane. Materials applied by this method include neoprene (with a protective layer of CSPE), silicone, polyurethane, butyl rubber, asphalt emulsion, and polymethyl methacrylate (PMMA).

Fluid-applied membranes are also used as a waterproofing layer over sprayed-on polyurethane foam insulation in roofing systems designed for surfaces that are hard to fit with flat sheets of insulation and membrane. These systems are also a convenient means for adding thermal insulation and a new roof membrane over existing but deteriorated built-up roofs on any shape of building.

Traffic Decks

Traffic decks are installed over flat roof membranes for walkways, roof terraces, and sometimes even vehicular driveways or parking surfaces. Two systems are used: In one, plastic pedestals are placed on top of the roof membrane to support the corners of square paving stones or slabs with open joints (Figure 17.17). In the other, a drainage layer of gravel or pervious concrete is leveled over the membrane, and open-jointed paving blocks are installed on top. In either system, water falls through the joints in the paving and is caught and drained away by the membrane below. Notice that the membrane is not pierced in either system. To protect the membrane from accidental damage, a protective layer made of additional roof membrane or other material is placed over the membrane before the traffic deck components are installed.

Roof Edge and Drainage Details

A watertight low-slope roof membrane installation includes the roof membrane itself, along with flashings at edges, penetrations, and corners. *Sheet metal flashings* are used to provide added physical protection at vulnerable edges, in applications where the flashing must be stiff enough to permanently hold a formed shape, or where a cleaner finished appearance is desired. *Membrane flashings* are made from the same (or similar) material as the roof membrane itself. Their greater flexibility in comparison to sheet metal flashings makes them useful for forming watertight seals at corners and penetrations, and at laps between the roof membrane and metal flashings or other materials.

Some typical slope roof details and components are illustrated in Figures 17.18 through 17.27. Most are shown with a single-ply, thermoset membrane that relies on adhesive to bond sheet edges and membrane flashings. When thermoplastic membranes are used, membrane materials are bonded by heat or chemical welding rather than adhesive. When multi-ply membranes are used, the overall approach to membrane and flashing detailing is the much the same as for single-ply systems, though with the additional, overlapping membrane plies that are a part of these systems.

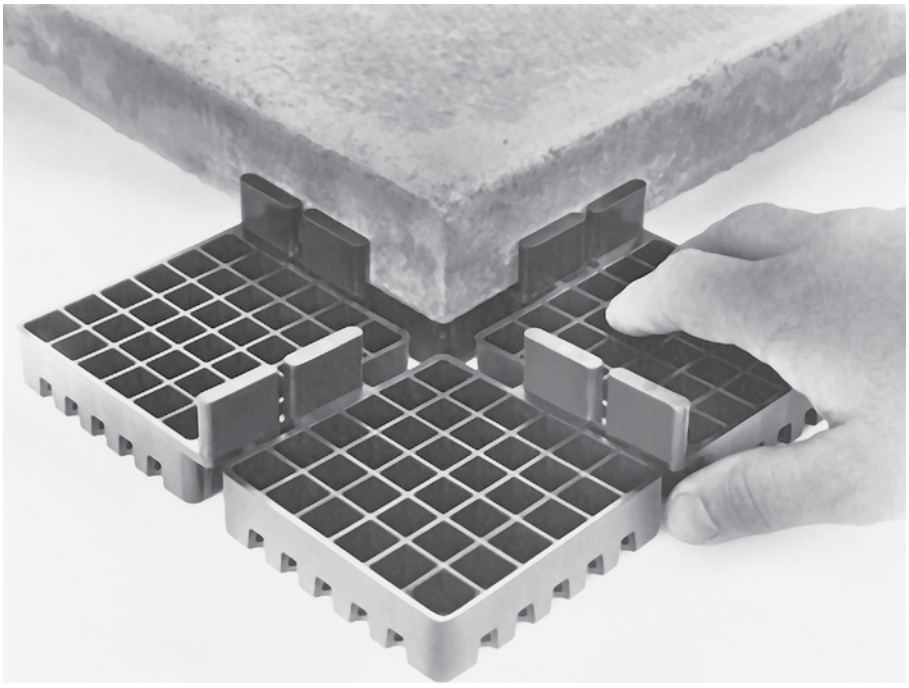


Figure 17.17
Plastic pedestals support stone or precast concrete paving blocks over a low-slope roof membrane, permitting the use of a low-slope roof as an outdoor terrace. Each high-density polyethylene pedestal supports the adjacent corners of four paving blocks. The vertical fins on the pedestal provide a uniform drainage space between the blocks. Matching polyethylene leveling plates (not shown) can be placed under the pedestals to compensate for irregularities in the roof surface. Adjustable-height pedestals that rely on threaded, telescoping sections are also available. *(Courtesy of Envirospec, Inc., Buffalo, NY.)*

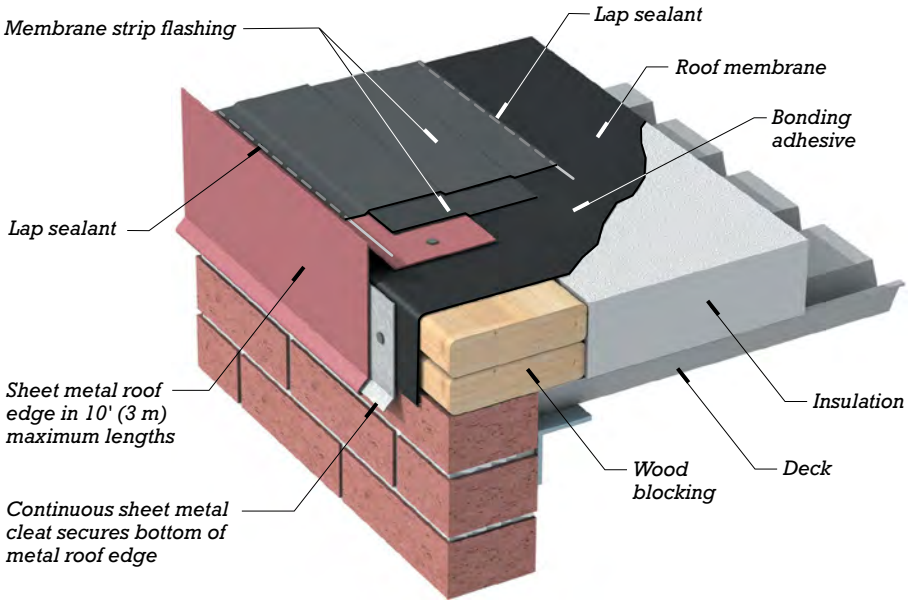


FIGURE 17.18
A simple roof edge for a single-ply, thermoset roof membrane. Membrane *strip flashings* (or *stripping*) create a watertight seal between the roof membrane and sheet metal components such as the metal roof edge shown here. Lap sealant at the edges of the membrane flashings prevents water from seeping through imperfections in the bond between flashing layers. Though not shown in this illustration, the roof surface slopes away from the roof edge toward an internal drain or scupper. The exposed vertical face of the sheet metal roof edge is called a *fascia*.

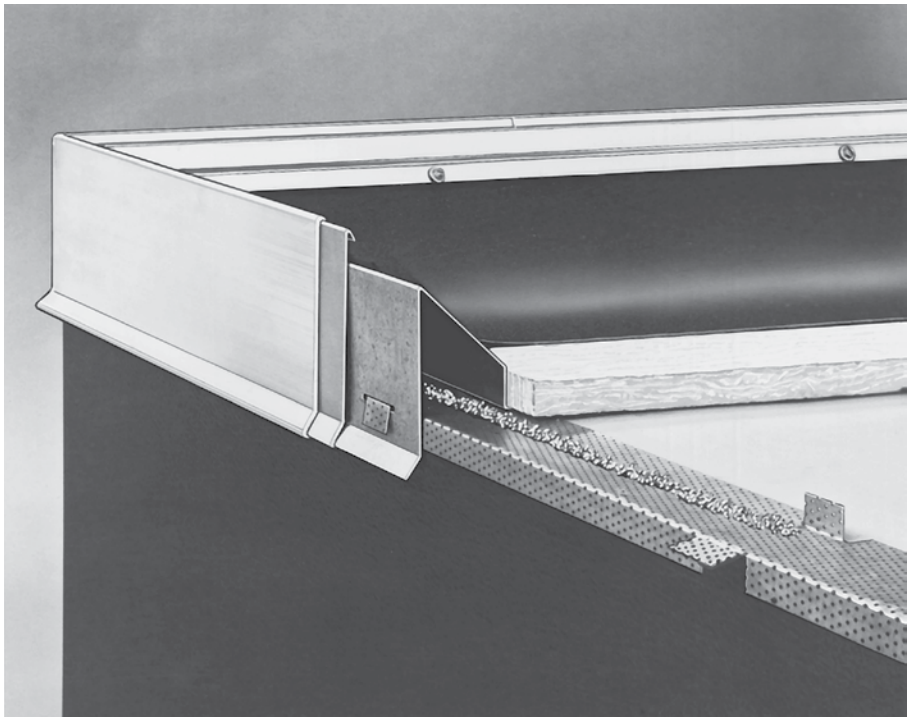


FIGURE 17.19
A roof edge system for low-slope roofs. The perforated metal strip is fastened to the roof with a mastic adhesive that oozes through the perforations to create a tighter bond. When the adhesive has hardened, a galvanized steel curb is fastened in place with the tabs of perforated metal and an aluminum roof edge is hooked on, with a backup piece at the end joints as shown to prevent leakage. Lastly, the roof edge and the membrane are locked in place simultaneously by installing a clamping strip that engages the hook on the top of the aluminum roof edge. The clamping strip is held in place by screws that pass through the edge of the membrane into the galvanized curb, as seen at the top of the photograph. (*Product of W. P. Hickman Company, Asheville, NC.*)

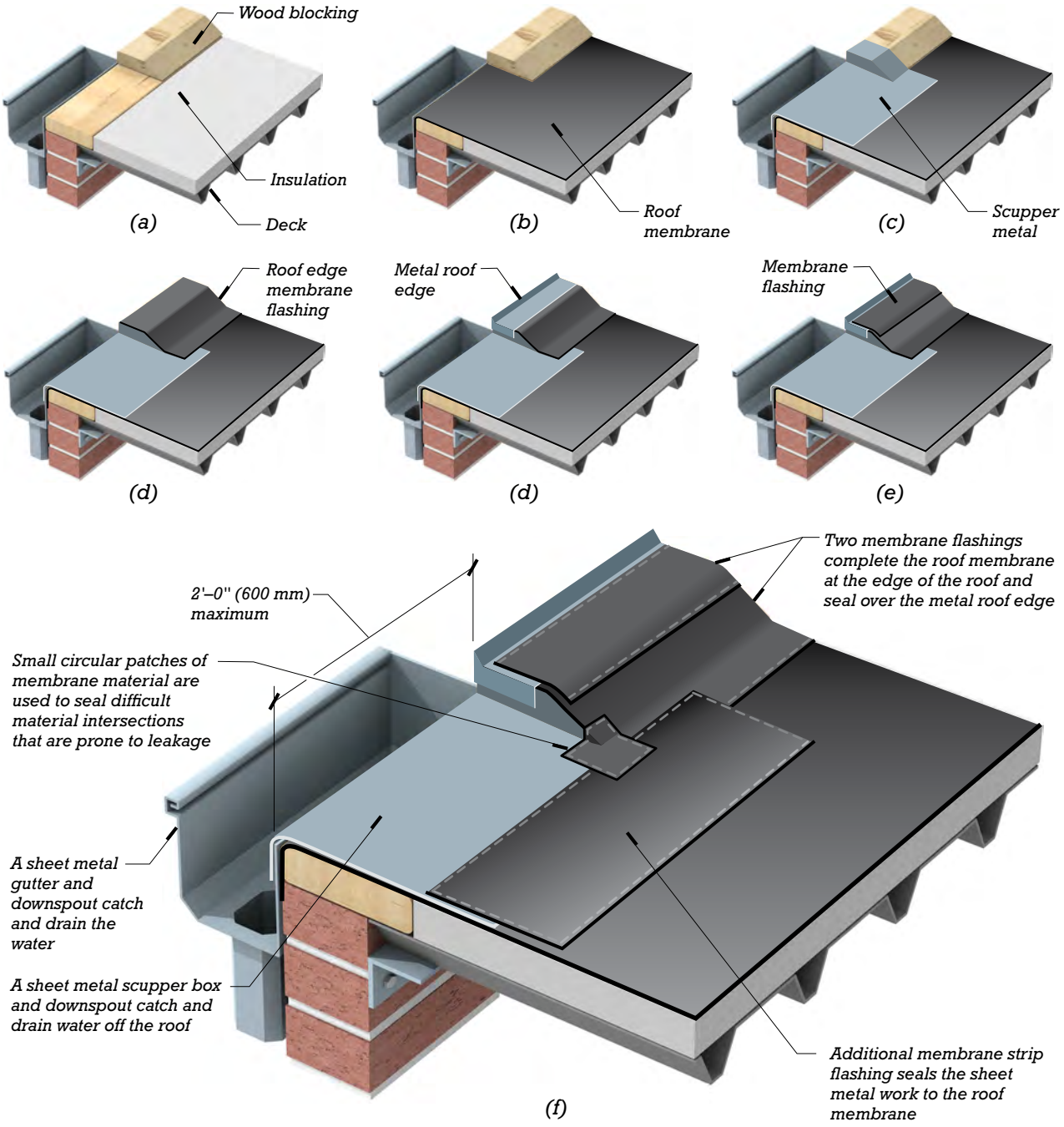


FIGURE 17.20
Detail of a *scupper*. The raised curb is discontinued to allow water to spill off the roof into a scupper box and downspout. Most roofs use interior drains (Figure 17.25) as their primary means of drainage, with scuppers more frequently used as secondary drainage to limit ponding in the case of a clog in the primary drain.

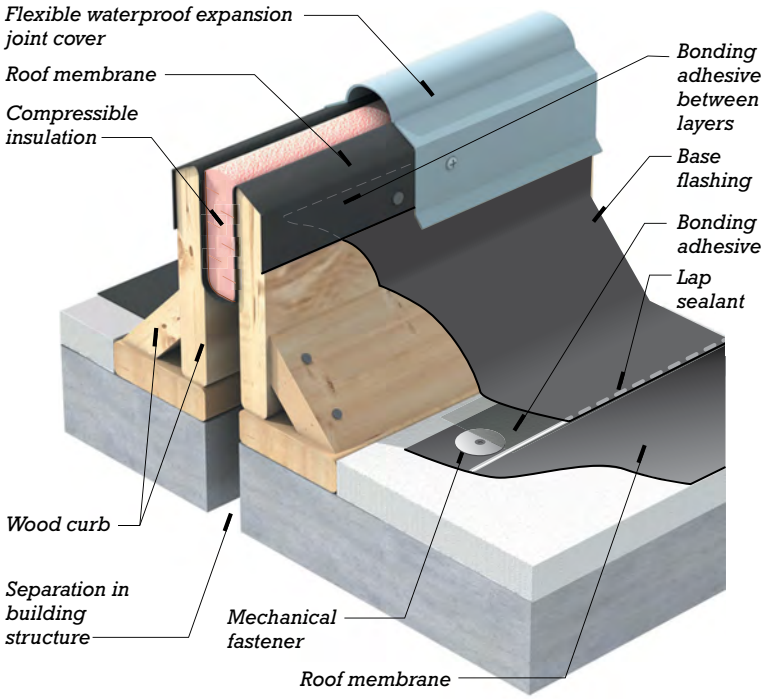


FIGURE 17.21
A building separation joint in a low-slope roof. Large differential movements between the adjoining parts of the structure can be tolerated with this type of joint because of the ability of the flexible joint cover and roof membrane draped within the joint to adjust to movement without tearing. High curbs keep water away from the top of the joint. Membrane flashings seal the roof membrane to the wood curbs. When flashings, such as these, seal between the roof membrane and vertical surfaces, they are called *base flashings*.

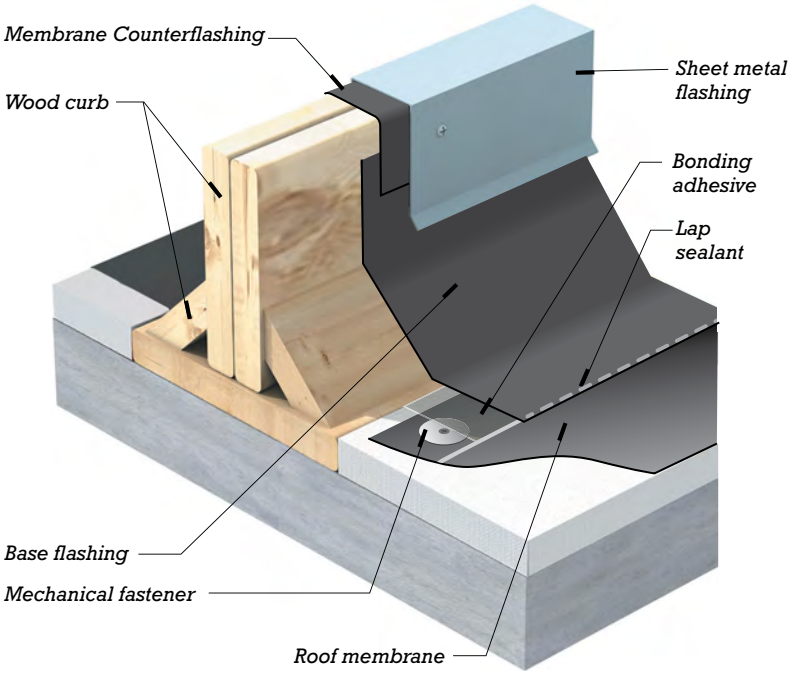


FIGURE 17.22
An area divider is designed to allow for movement only in the membrane itself, but not in the structure below. It is used to subdivide a very large membrane to allow for thermal movement or material shrinkage.

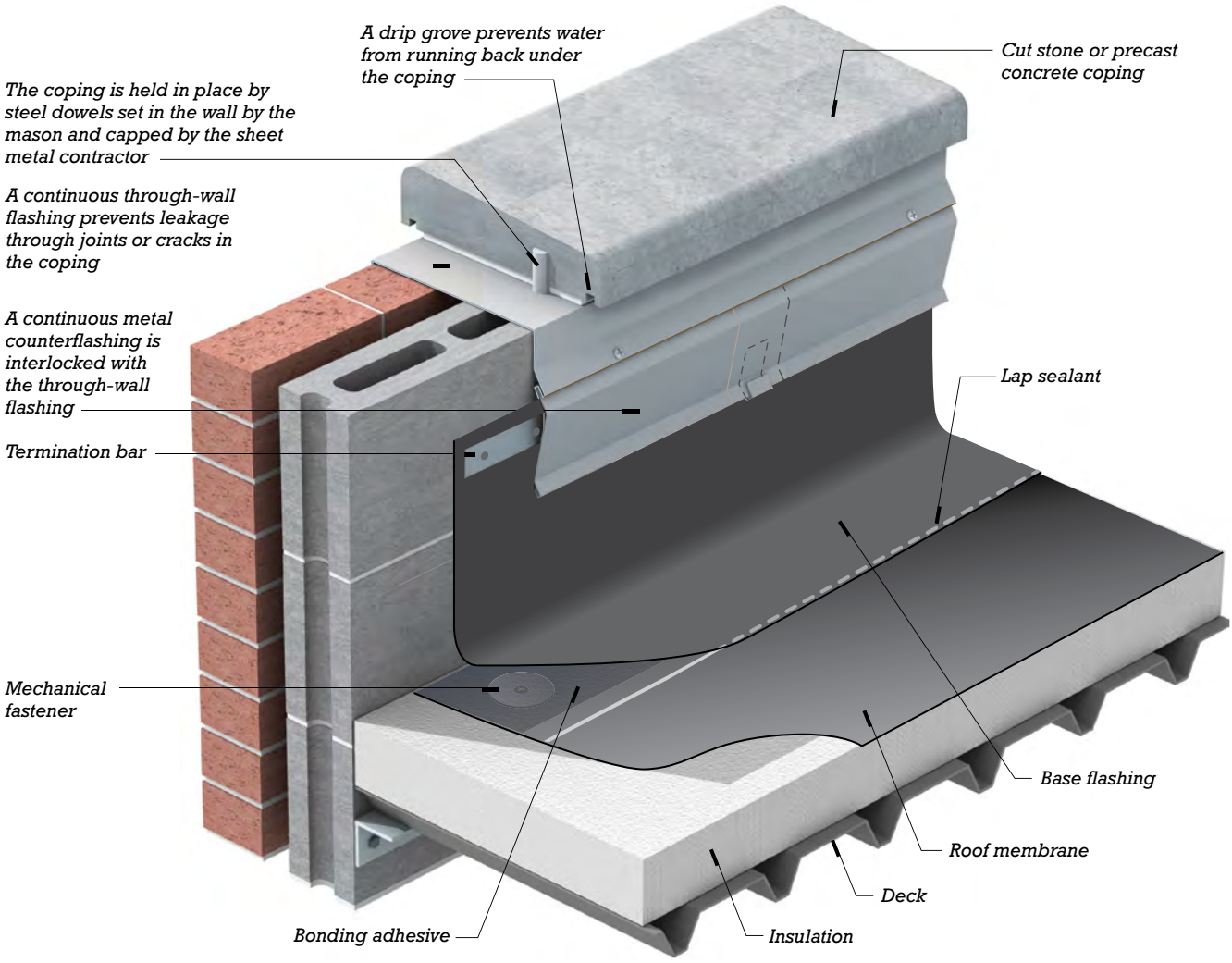


FIGURE 17.23
A *parapet*—a low wall that projects above the roof edge—with sheet metal through-wall flashing and stone *coping*. A sheet metal *counterflashing* prevents water from seeping behind the vertical termination at the top of the base flashing. It is designed for easy removal in the future event of roof replacement.

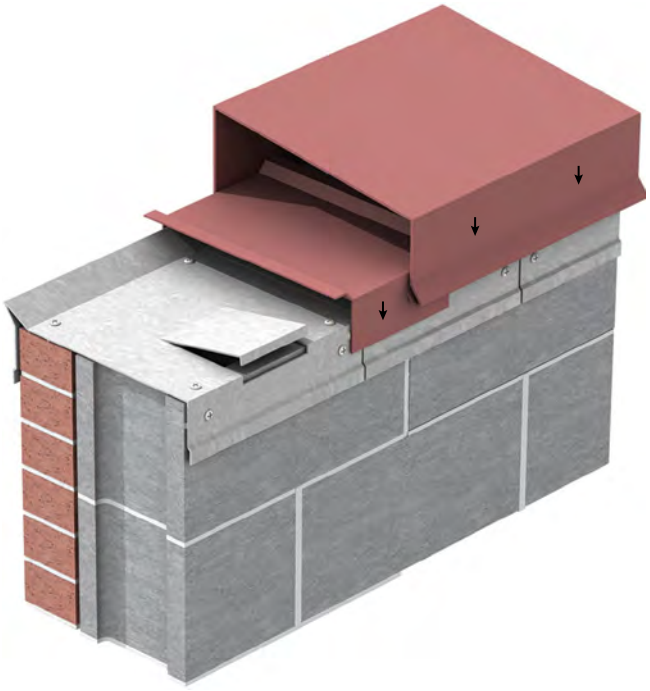


FIGURE 17.24
A parapet coping system. Metal cleats, about 12 inches (300 mm) long, are fastened to the top of the wall at regularly spaced intervals. Sections of metal coping are snapped over the cleats. Specially formed pan elements located beneath the coping joints ensure that water that leaks between coping joints drains to the exterior. *(Product of W. P. Hickman Company, Asheville, NC.)*

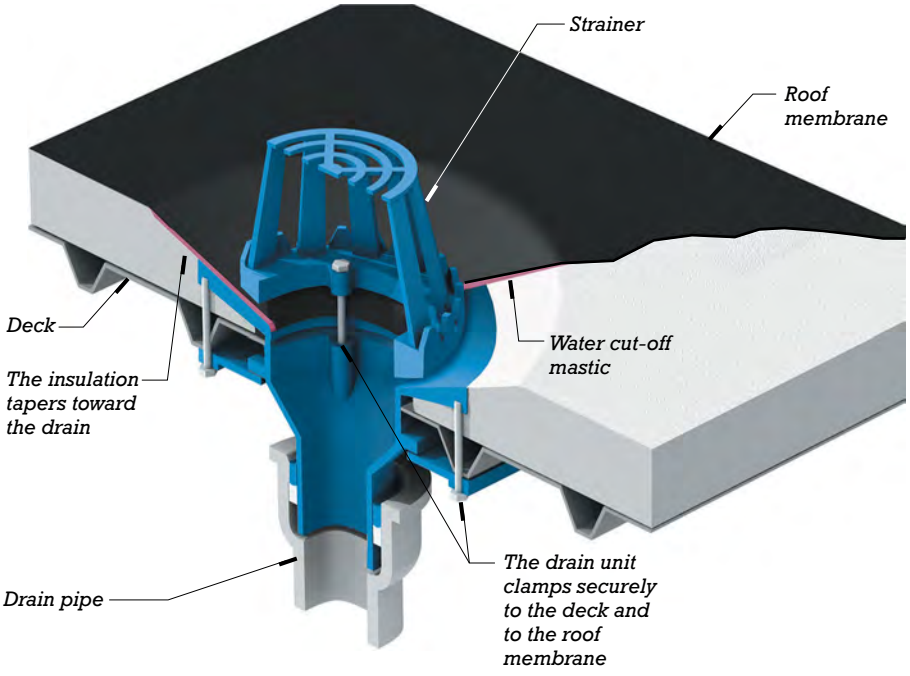


FIGURE 17.25
A cast iron interior *roof drain* for a low-slope roof. The roof membrane is clamped directly into the drain body.

FIGURE 17.26
A single-piece roof drain made of molded plastic. *(Product of W. P. Hickman Company, Asheville, NC.)*

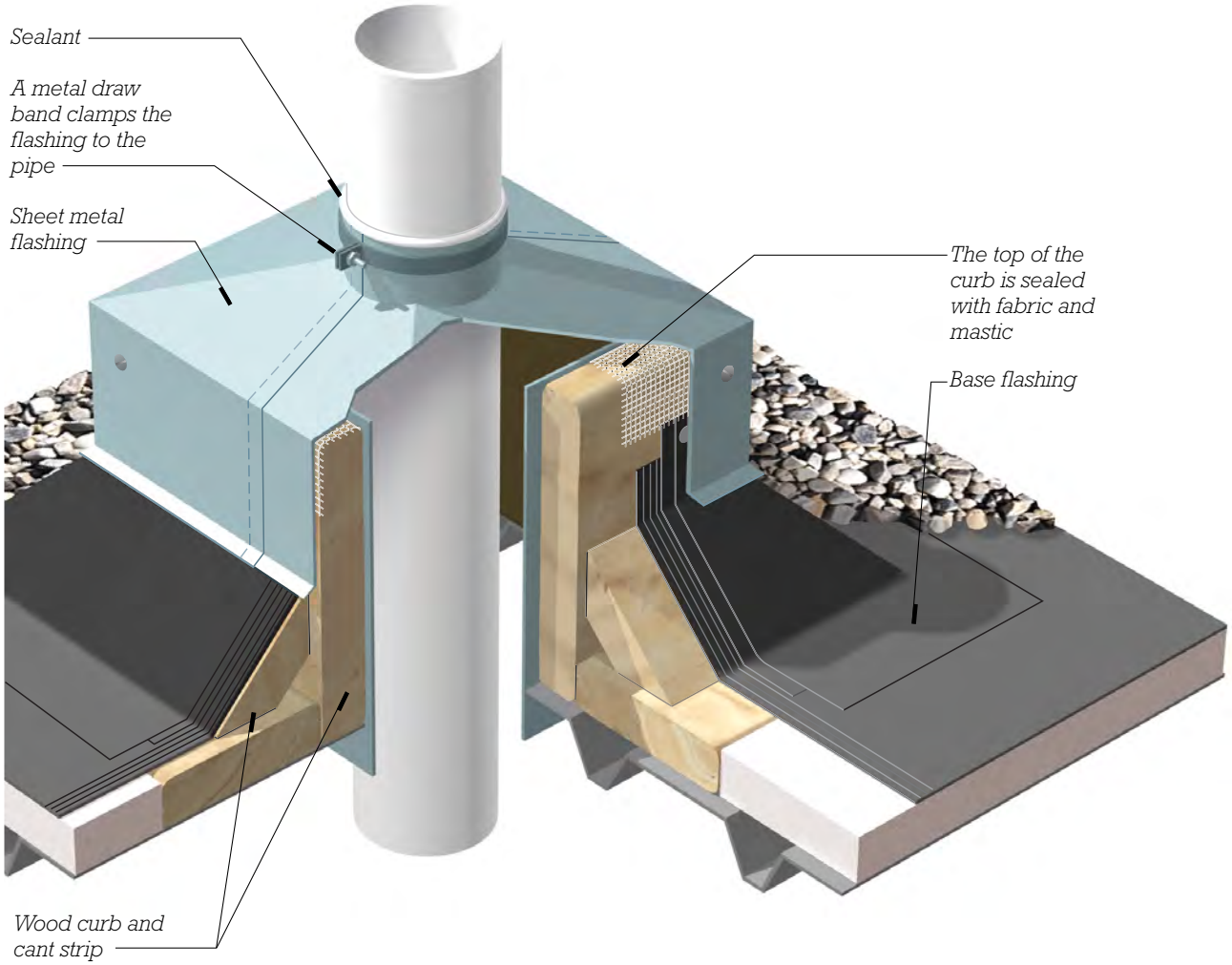


FIGURE 17.27
A *roof penetration* for a plumbing vent stack, with a multi-ply built-up roof membrane. Notice the more complex layering of roofing plies and membrane flashing. In multi-ply roofs, *cant strips* at horizontal to vertical transitions play an important added role, transforming sharp right-angle bends into a pair of 45-degree bends that place less stress on these less pliable membrane types.

Structural Metal Panel Roofing

Structural metal panel roofing is made from sheets of steel or aluminum, formed into long, narrow ribbed or corrugated panels. The panels are stiff enough to span between supports, called *purlins*, spaced as much as 8 feet (2.4 m) on center, or they may be installed over continuous roof decks. Panels with watertight seams and concealed fastening systems can be installed with slopes as shallow as ½:12 (1 in 24) or ¼:12 (1 in 48) (Figures 17.28, 17.29, and 17.30). For more information about different metals used in metal roofing, see "Architectural Sheet Metal Roofing" later in this chapter.

Structural metal panels may also be used to clad steep roofs and walls (Figure 17.31). The corrugated metal panels in this figure are attached to supporting purlins with exposed mechanical fasteners rather than concealed metal clips. Resilient washers under each fastener head minimize the chance of water leakage through the fastener holes in the panels.

Figure 17.28
As a first step in reroofing a building with a structural metal roof, steel Z-purlins are erected over the old roof on tubular metal posts. *(Courtesy of Metal Building Manufacturers Association.)*

FIGURE 17.29
A metal clip is used to fasten the metal roofing sheets to the Z-purlins while allowing for thermal movement in the sheets. The plastic foam collar avoids thermal bridging. *(Courtesy of Metal Building Manufacturers Association.)*

FIGURE 17.30
The completed structural metal roof has a slope of only ¼:12 (1:48). The numerous penetrations for plumbing vents, air vents, and ductwork are typical of low-slope roofs. *(Courtesy of Metal Building Manufacturers Association.)*

Steep Roofs

Roofs with pitches of 2:12 to 3:12 (1 in 6 to 1 in 4) or greater are referred to as *steep roofs*. Traditional *thatch*, occasionally still used for the restoration of historic structures, is an attractive and effective, but highly labor intensive, roofing material consisting of bundles of reeds, grasses, or leaves (Figures 17.1 and 17.2). Modern steep-slope shingle and sheet metal roofs of many types are common to every type of building and range from the most economical roof coverings to the most durable and costly.

Strategies for insulating steep roofs, and the placement of air barriers and vapor retarders for them, are essentially the same as those for low-slope roofs, as illustrated in Figure 17.3 and discussed in the accompanying text. Further examples are illustrated and discussed in Chapters 6 and 7.

In cold climates, steep roofs may have a tendency to form ice dams at the eaves under wintertime conditions. Where the risk of ice damming is high, building codes require rubberized underlayment or other ice barrier material along the eaves to prevent trapped water from entering the building (see Chapter 6).

Figure 17.31
A lightweight steel Quonset hut structure is clad with curved corrugated metal roof panels and straight corrugated wall panels. *(Photo by Joseph Iano.)*

Shingles

The word *shingle* is used here in a generic sense to include wood shingles and shakes, asphalt shingles, slates, clay tiles, and concrete tiles. What these materials have in common is that they are applied to the roof in small, overlapping units with staggered vertical joints.

Wood shingles are thin, tapered slabs of wood sawn from short sections of logs with the grain of the wood running approximately parallel to the face of the shingle (Figure 17.56). *Wood shakes* are thicker than shingles, exhibit a rougher texture, and may be split from the wood rather than sawn. Most wood shingles and shakes in North America are made from red cedar, white cedar, or redwood to take advantage of these woods' natural decay resistance.

Traditionally, wood shingles and shakes were installed over *skip sheathing* (*spaced sheathing*), or spaced boards running perpendicularly across the sloped roof rafters. Skip sheathing allows air flow underneath the shingles that prevents condensation and deterioration of the shingles (Figure 17.32). When applied over continuous, solid sheathing, airflow underneath the wood shingles and shakes can be provided by adding spaced wood strips over the sheathing or with a *breather*

Figure 17.32
Wood shingles applied over skip sheathing, as seen from below. Even without a continuous roof sheathing or roofing underlayment, this shingle installation provides reliable protection from the weather. *(Photo by Joseph Iano.)*

FIGURE 17.33
Wood shingles and shakes are installed so that any part of the roof is always covered by at least three shingles. Coverage recommendations also vary with the slope of the roof and the quality of the wood used in the shingles or shakes. *(Photo by Joseph Iano.)*

mat, a wiry plastic mat placed under the shingles that creates a thin airspace. Wood roof coverings are moderately expensive and are not highly resistant to fire unless the shakes or shingles have been treated with fire-retardant chemicals. They eventually fail from erosion of the wood fibers and may be expected to last 15 to 25 years under average conditions (Figures 17.33 and 17.34).

Asphalt (or *composition*) *shingles* are die-cut from heavy sheets of asphalt-impregnated felt faced with mineral granules to act as a wearing layer and decorative finish. Most felts are based on glass fibers, but some still retain the older cellulose composition. The most common type of asphalt shingle, which covers probably 90 percent of the single-family houses in North America, is 12 inches × 36 inches (305 mm × 914 mm) in size. (A metric-size shingle 337 mm × 1000 mm is also widely marketed.) In the most popular pattern, each shingle is slotted twice to produce a roof that looks as though it were made of smaller shingles (Figures 17.35 through 17.39). Other sizes and many other styles are available, including thicker shingles that are laminated from several layers of material. Asphalt shingles are inexpensive to buy, quick to install, moderately fire-resistant, and have a life expectancy of 15 to 25 years.

The same sheet material from which asphalt shingles are cut is also manufactured in rolls 3 feet (914 mm) wide as asphalt *roll roofing*. Roll roofing is inexpensive and is used primarily on utility and agricultural buildings. Its chief drawbacks are that thermal expansion of the roofing or shrinkage of the wood deck can cause unsightly ridges to form in the roofing and that thermal contraction can tear it.

Slate shingles for roofing are delivered to the site split, trimmed to size, and punched or drilled for nailing (Figures 17.40 and 17.41).

FIGURE 17.34
Shake installation over a new roof deck. Strips of asphalt-saturated felt have been placed in advance with their lower edges unfastened. Each course of shakes is laid out, slipped up under its felt strip, then quickly fastened with pneumatic powered staplers as the roofers walk across the roof. *(Courtesy of Senco Products, Inc.)*

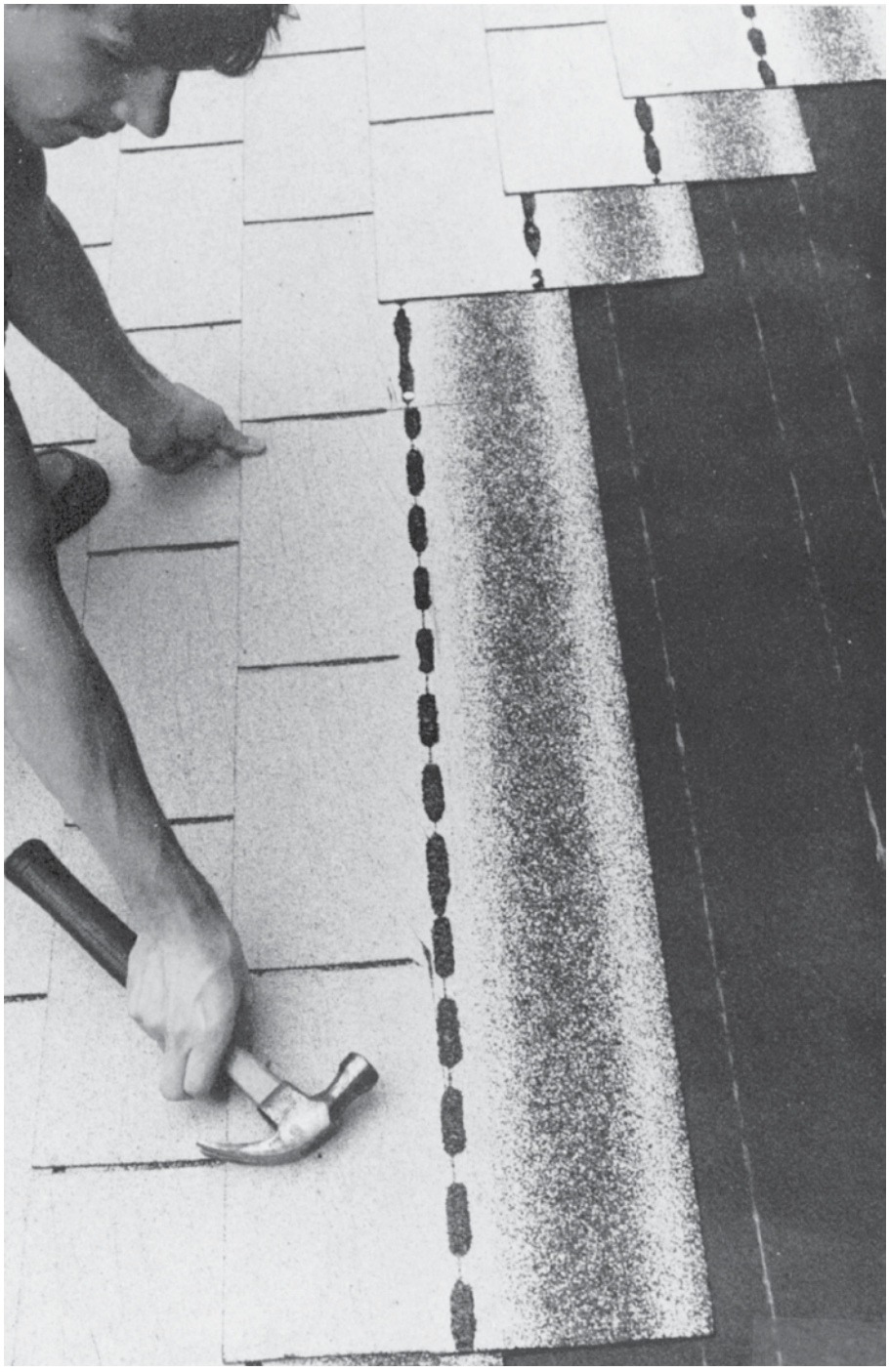


FIGURE 17.35
Installing asphalt shingles. To give a finer visual scale to the roof, the slots make each shingle appear to be three smaller shingles when the roof is finished. Many different patterns of asphalt shingles are available, including ones that do not have slots. *(Photo by Edward Allen.)*

They form a fire-resistant, long-lasting roof. Although first costs are high, slate roofs can last 60 to 80 years.

Clay tiles have been used on roofs for thousands of years. It is said that the tapered barrel tiles traditional to the Mediterranean region (similar to the mission tiles in Figure 17.42) were originally formed on the thighs of the tilemakers. Many other patterns of clay tiles are available, both glazed and unglazed. *Concrete tiles* are generally less expensive than those of clay. Tile roofs are heavy, durable, highly resistant to fire, and relatively expensive in first cost. Expected lifetimes range from 30 to 75 years, depending on climate and the resistance of the tiles to water absorption.

Other materials used for roof shingles include sheet metal, rubber, fiber-reinforced cement, and plastic. Each type of shingle must be laid on a roof deck that slopes sufficiently to ensure leakproof performance. Minimum slopes for each material are specified by the manufacturer and the building codes. The minimum slope for a standard asphalt shingle roof is usually 4:12 (1 in 3); or, with special protective underlayments, slopes as low as 2:12 (1 in 6) may be acceptable in some circumstances. For any shingle type, slopes greater than the minimum can better resist leakage from water driven up the roof surface by heavy winds.

FIGURE 17.36
Laminated asphalt shingles create a pleasing, textured roof surface. The cupola roof is copper sheet metal with standing seams. *(Photo by Joseph Iano.)*

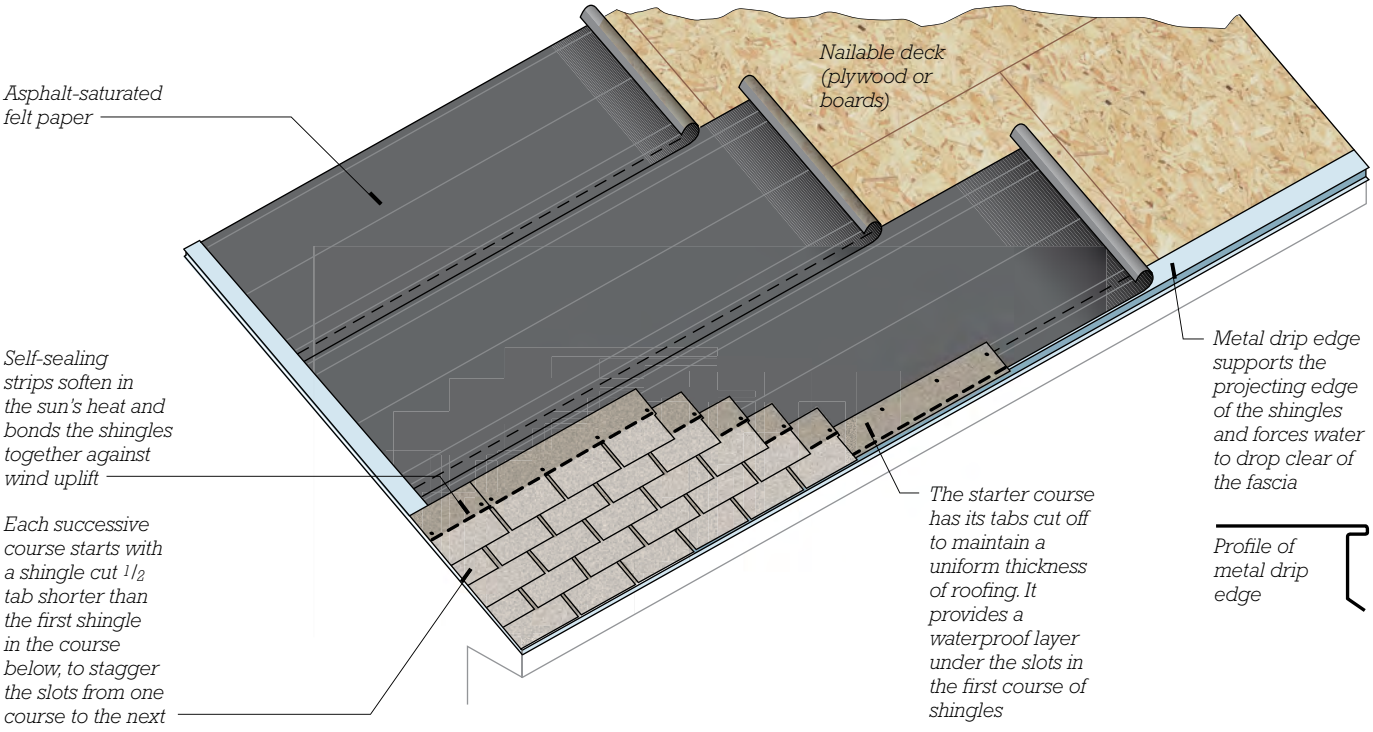


FIGURE 17.37
Starting an asphalt shingle roof. As explained in Chapter 6, building codes require the installation of an ice barrier beneath the shingles along the eave in regions with cold winters, where roofs are prone to ice damming. Where required, the ice barrier would replace the lowest course of asphalt-saturated felt paper shown in this illustration.

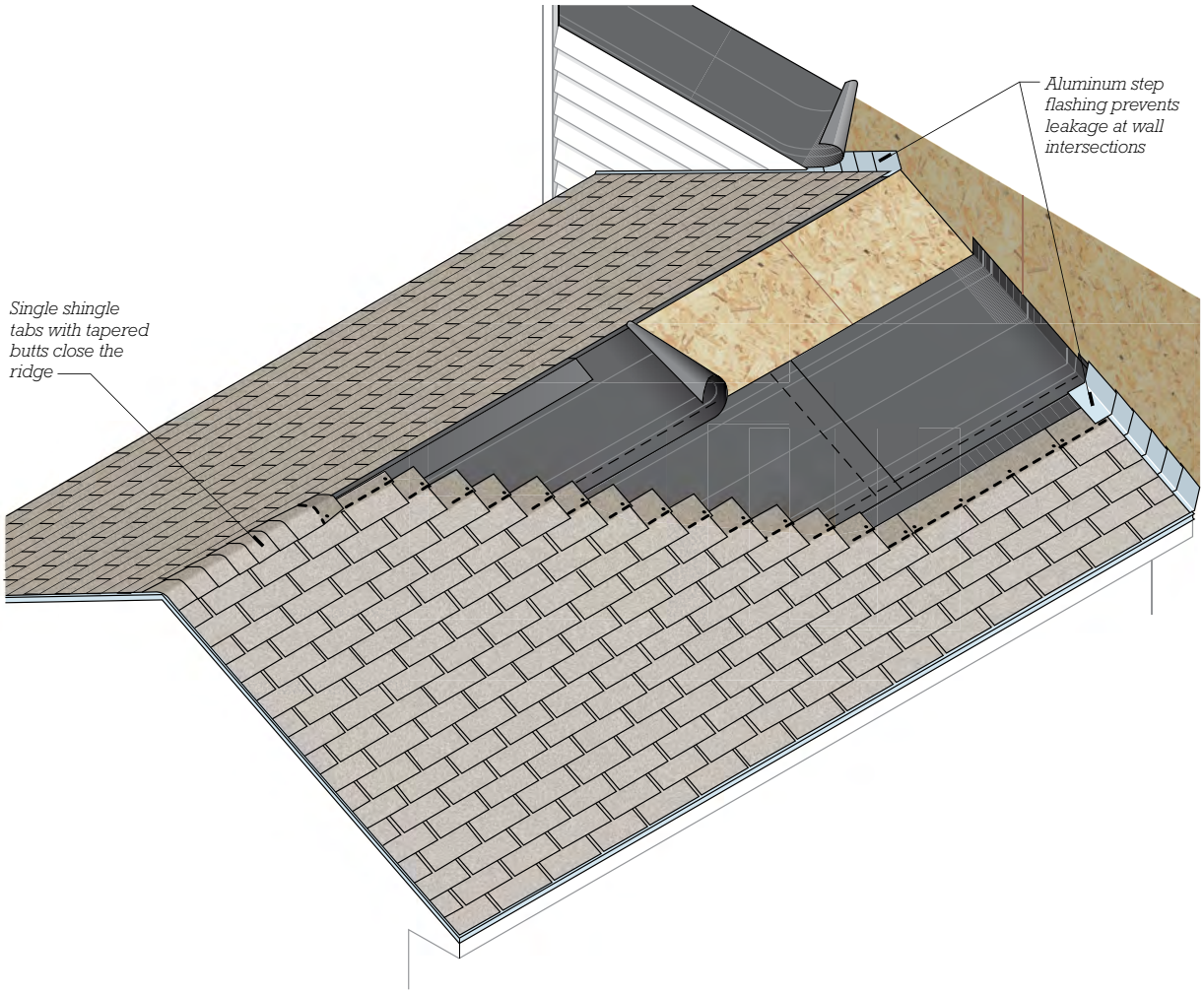
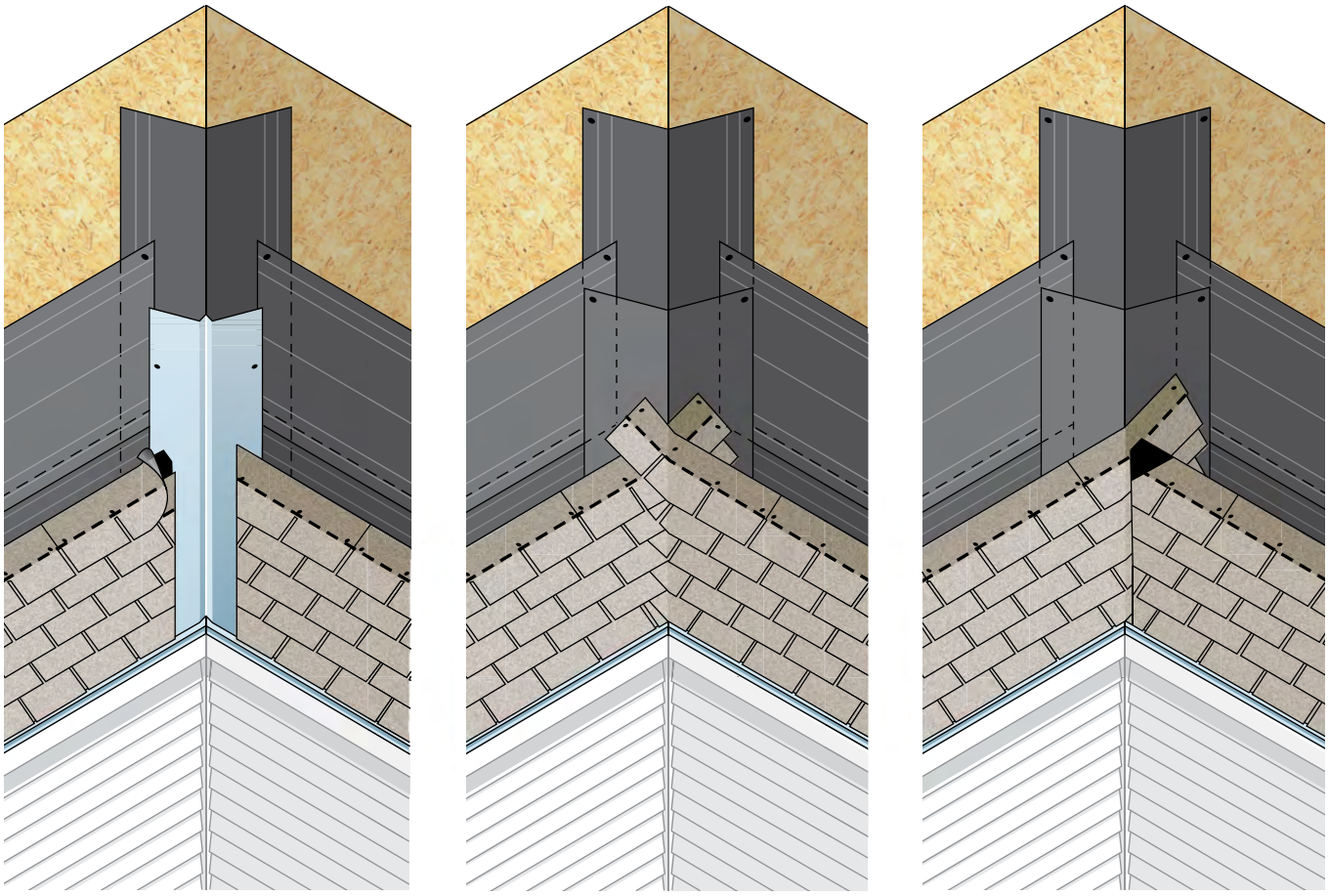


FIGURE 17.38
Completing an asphalt shingle roof. A metal or plastic ridge vent strip (see Chapter 6) is often substituted for the shingle tabs on the ridge to provide an outlet for ventilation under the roof sheathing.



A. OPEN VALLEY B. WOVEN VALLEY C. CLOSED CUT VALLEY

FIGURE 17.39

A *valley* is formed in a roof where two sloping roof planes meet above an inside corner of the building. Three alternative methods of making a valley in an asphalt shingle roof are shown here. (*A*) The *open valley* uses a sheet metal flashing; the ridge in the middle of the flashing helps prevent water that is coming off one slope from washing up under the shingles on the opposite slope. The *woven valley* (*B*) and *cut valley* (*C*) are favorites of roofing contractors because they require no sheet metal. The solid black areas on shingles in the open and cut valleys indicate areas to which asphaltic roofing cement is applied to adhere shingles to each other.

Figure 17.40
Splitting slate for roofing. The thin slates in the background will next be trimmed square and to dimension, after which nail holes will be punched in them. *(Photo by Flournoy, courtesy of Buckingham-Virginia Slate Corporation.)*

Figure 17.41
A slate roof during installation. *(Courtesy of Buckingham-Virginia Slate Corporation.)*

Architectural Sheet Metal Roofing

Unlike the structural metal panel roof discussed earlier in this chapter, *architectural sheet metal roofing* must have a continuous, solid structural substrate for support. It is made from thin sheets of metal using ingenious systems of joining and fastening to maintain watertightness. Seams must be spaced closely enough to secure the sheets against wind uplift and minimize *oil canning* (unsightly waviness). The seaming configurations also create strong visual patterns that contribute to the architectural expression of the roof.

The minimum recommended slope for architectural sheet metal roofing is 1:12 for standing-seam roofing and 3:12 (1 in 4) for flat-seam or batten-seam roofing. In some configurations, lower slopes can be achieved by adding extra waterproofing layers below the sheet metal, making seams taller, soldering seams, or treating seams with elastomeric sealant.

Architectural Sheet Metal Roofing Types

Three standard configurations—*standing seam*, *flat seam*, and *batten seam*—are illustrated in Figures 17.43 through 17.49. Architectural sheet metal roofing is relatively high in first cost, but also long-lasting.

Sheet Metal Roofing Materials

Many types of metal may be used in the production of architectural sheet metal roofs:

- *Lead* is a soft, easily formed, long-lasting metal that oxidizes over time to a dull white color. It is also toxic to humans. Today, it (and lead-coated copper) are used primarily for replacement of existing, like materials in historic preservation work.
- *Copper* is a long-lasting, relatively soft metal that turns a beautiful blue-green in clean air and a darker black in an industrial atmosphere. Chemical treatments can be used to obtain and preserve the desired color.
- *Zinc* is a long-lasting sheet metal made of zinc alloyed with small amounts of copper and titanium to improve its workability. It normally ages to a dark gray color and can also be treated in various ways to alter or preserve its appearance.

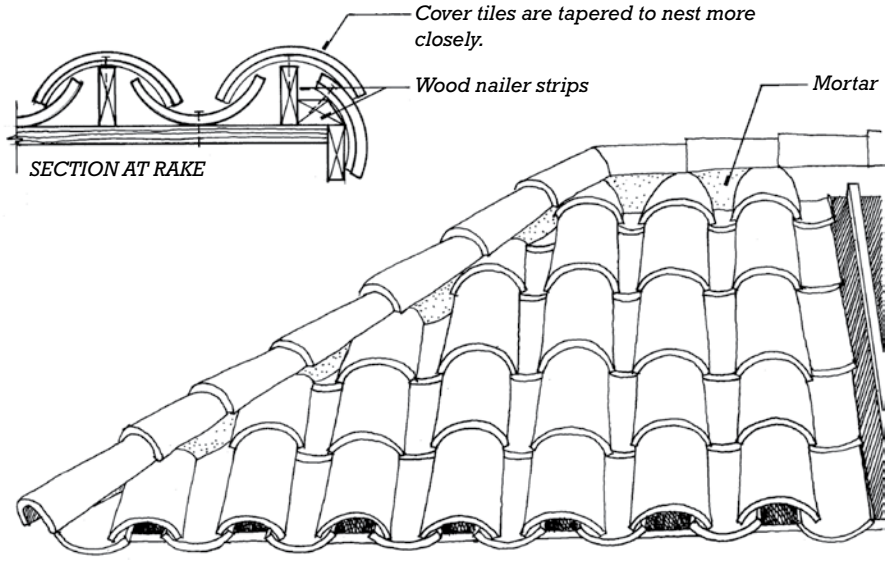
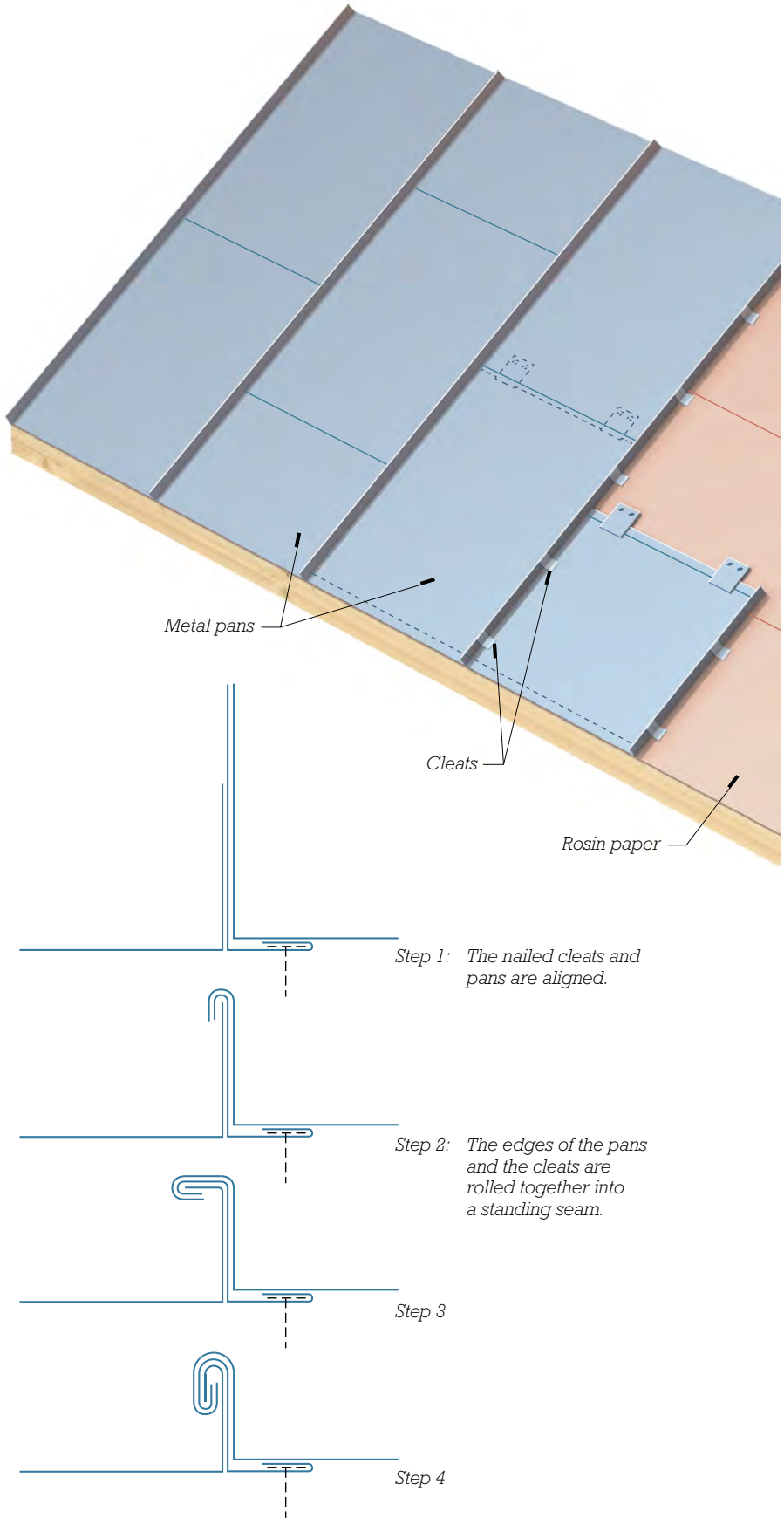


FIGURE 17.42
Two styles of clay tile roofs. The mission tile has ancient origins.



- *Stainless steel* and *titanium* are strong and long-lasting but less easily worked than other roofing metals. Both are silvery-white.
- *Zinc-tin alloy coated stainless steel* has a darker, duller appearance than uncoated stainless steel. This material is very similar in appearance to a lead-tin alloy coated metal called *terne-coated stainless steel* that is no longer manufactured but may still be found on older buildings.

The metals in the preceding list all form self-protecting oxide coatings that provide long-lasting resistance to corrosion. They are usually installed uncoated and allowed to weather naturally, gradually achieving their final appearance, or *patina*. Other, less expensive metals, which are not as long-lasting in an uncoated condition, are also used for sheet metal roofing. They are commonly factory-coated with organic (paint-like) coatings that extend their life expectancy and provide a wide range of color choice. These include *aluminum* and *metallic-coated steel* (steel coated with alloys of zinc or zinc-aluminum). For more information about architectural metals, see Chapter 12.

FIGURE 17.43
Standing-seam metal roofing. The four diagrams at the bottom of the illustration show the steps in the forming the panel seams, viewed in cross section. The cleats, which are fastened to the roof deck and hold the panels in place, are completely concealed in the finished installation. To guard against leakage through seams at lower slopes, standing seams may be made taller or sealed with elastomeric sealant.

FIGURE 17.44
A sheet metal installer forms standing-seam pans at the construction site from a coil of copper sheet metal and a portable pan-forming machine mounted in the back of a pickup truck. *(Photo by Joseph Iano.)*

FIGURE 17.45
On the roof an automatic roll seamer, moving under its own power, folds the standing seams in a copper roof. A cleat is just visible toward the lower right. *(Photo courtesy of DBI/SALA, Red Wing, MN; courtesy of Copper Development Association, Inc.)*

FIGURE 17.46
Finished standing-seam copper roofing.
(Designer: Emil Hanslin. Courtesy of Copper Development Association, Inc.)

FIGURE 17.47
The standing-seam roof panels for the International Center in Brattleboro, Vermont, were factory-formed and shipped to the construction site already in their final profile.

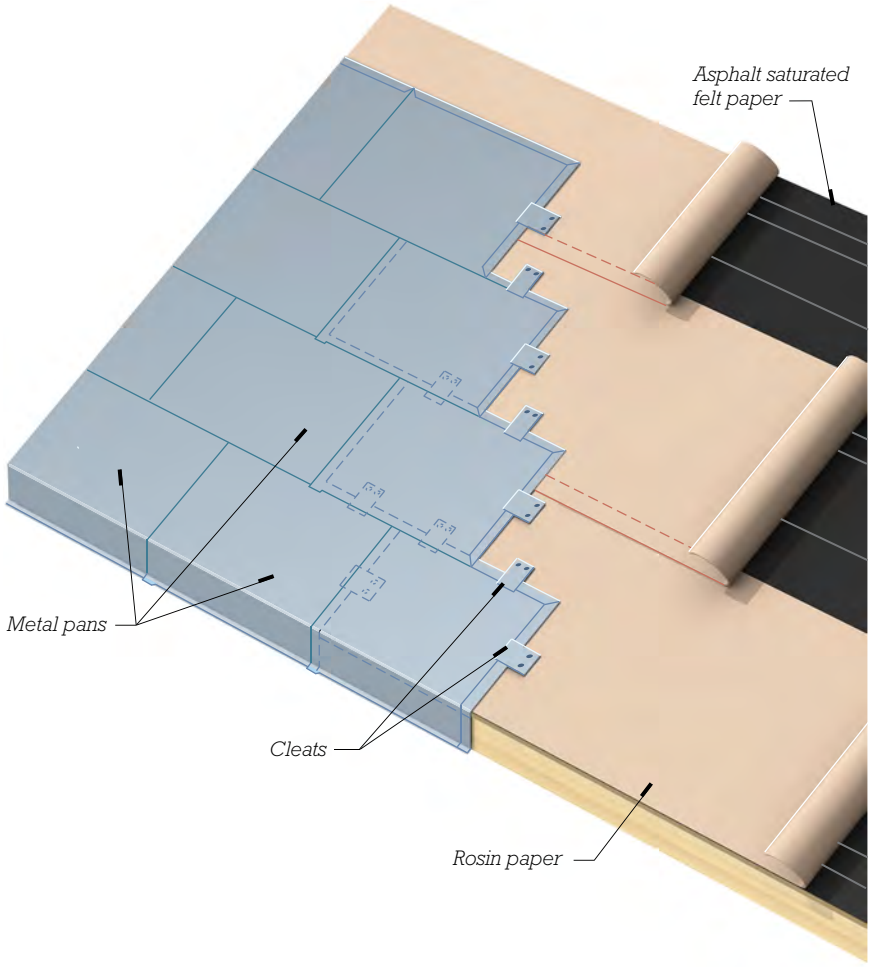
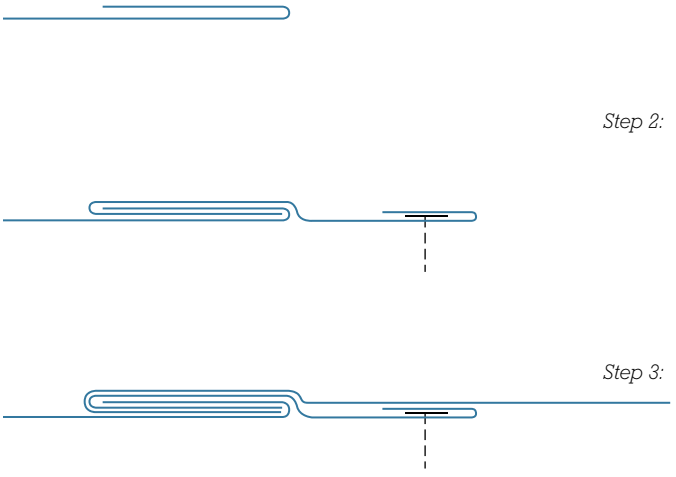


FIGURE 17.48
Flat-seam metal roofing. To ensure that seams remain watertight, they are sealed with elastomeric sealant. Or for low slopes, the seams are soldered.



Step 1: *Each pan is formed in the sheet metal shop with folded edges.*

Step 2: *Sheet metal cleats interlock with the folded edges and are nailed to the deck. The cleat is folded back over the nail head to protect the pan.*

Step 3: *The next pan is interlocked with the first. When all pans are in place, the edges are beaten flat and soldered or sealed.*

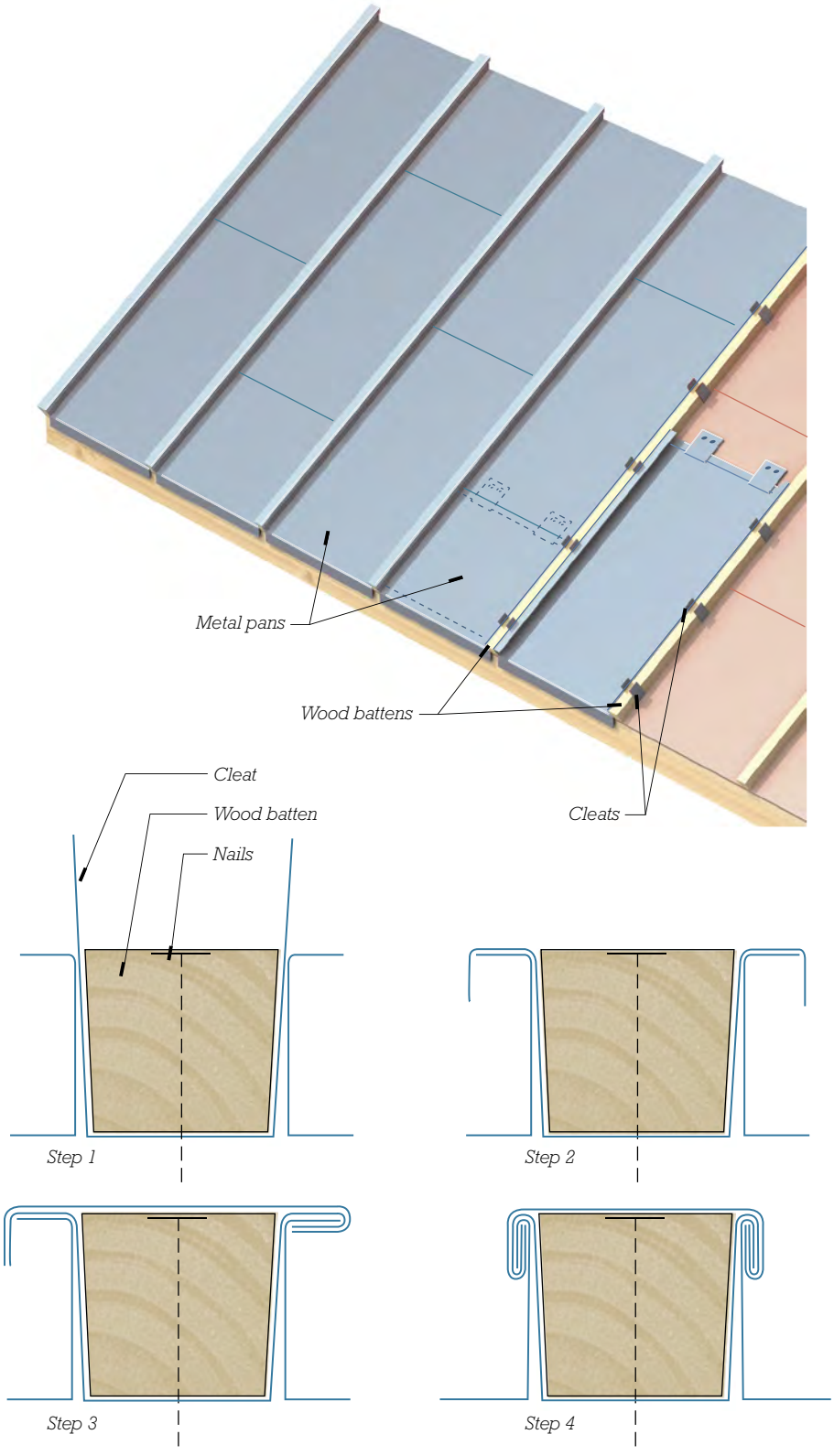


FIGURE 17.49
Batten-seam metal roofing. The battens are tapered in cross section to allow for expansion of the roofing metal. For low slopes, seams may be sealed with elastomeric sealant.

Sheet Metal Thickness

Methods for describing sheet metal thickness differ among metal types. Traditionally, steel sheet metal thickness is described by *gauge* (also spelled *gage*), a system of whole numbers in which lower numbers correspond to greater metal thickness. While the use of gauge numbers persists, lack of uniformity in the translation between gauge and actual thickness has lead standards-setting groups to switch to describing steel sheet metal thickness in decimal inches. At this time, both methods are used. The thickness of aluminum sheet metal is always described in decimal inches, and copper in weight per square foot. Generally, thicker sheets are stronger, stiffer, more resistant to oil canning, and more durable. Thinner sheets are easier to form and less costly. Figure 17.50 lists typical thicknesses for some sheet metal roofing materials.

		Nominal Thickness	
Steel Sheet	**Gauge**	**Metallic-Coated Steel**	**Stainless Steel**
	18	0.052 in.	0.050 in.
		1.32 mm	*1.27 mm*
	20	0.040 in.	0.038 in.
		1.02 mm	*0.95 mm*
	22	0.034 in.	0.031 in.
		0.86 mm	*0.79 mm*
	24	0.028 in.	0.025 in.
		0.71 mm	*0.64 mm*
	25	0.025 in.	0.022 in.
		0.64 mm	*0.56 mm*
	26	0.022 in.	0.019 in.
		0.56 mm	*0.48 mm*
Copper Sheet	**Weight per sq. ft. (0.092 m²)**	**Nominal Thickness**	
	24 oz.	0.032 in.	
		0.82 mm	
	20 oz.	0.027 in.	
		0.68 mm	
	16 oz.	0.022 in.	
		0.55 mm	
Aluminum Sheet		**Nominal Thickness**	
		0.060. in	
		1.52 mm	
		0.050 in.	
		1.27 mm	
		0.040 in.	
		1.02 mm	
		0.032 in.	
		0.81 mm	

FIGURE 17.50
Thicknesses of sheet metals commonly used in architectural sheet metal roofing.

Protection from Corrosion between Dissimilar Metals

When different metals come in contact with the presence of moisture, *galvanic corrosion* can occur. This type of corrosion, and strategies for managing it, are discussed in greater detail in the accompanying sidebar. Where possible, using the same metal for all parts of the roofing system can avoid this phenomenon. However, this is not always possible, and where different metals are used together, care must be taken to avoid unintended accelerated corrosion of some components.

COOL ROOFS

Roofs are exposed to solar radiation daily. As that radiation is absorbed and converted to heat, the temperature of the roof covering rises, routinely reaching temperatures of 150 degrees Fahrenheit (65°C) or higher. High roof temperatures can lead to overheating of interior spaces; reduced comfort for building occupants; increased building energy consumption; the need for larger, more expensive cooling equipment; shortened life span of roofing materials; and an increased contribution to urban heat island effects through elevation of the surrounding air temperature. Selecting a *cool roof* covering that minimizes such heating can reduce these effects.

Solar heating of roofs is principally affected by two properties of the roofing material. A material's *solar reflectance*, or *albedo*, is a measure of its tendency to reflect solar radiation rather than absorb it. Solar reflectance is measured on a unitless scale from 0 to 1, where 1 represents a material that reflects all solar radiation and 0 represents one that absorbs all such radiation. A higher solar reflectance corresponds to a cooler roof. *Thermal emittance* is a measure of a material's capacity to

radiate infrared heat energy and cool itself as its temperature rises. Like solar reflectance, thermal emittance is measured on a scale of 0 to 1, and a higher thermal emittance implies a cooler roof.

Cool roof criteria differ among green building programs. Requirements for the EPA Energy Star program are based solely on a roof covering's solar reflectance. Requirements for LEED are based on a roof covering's *solar reflective index* (*SRI*). SRI is a measure of solar heating potential that accounts for a material's reflective and emittive properties, as well as its ability to lose heat through thermal conductance to the surrounding air. Two roofing materials with the same SRI are expected to achieve the same surface temperature under similar exposures. Higher SRI values correspond to cooler roof coverings, with an SRI value of 0 corresponding to a standard reference black surface and a value of 100 corresponding to a reference white surface (Figure 17.51).

Comparative solar heating properties for some sample roofing materials are listed in Figure 17.52. In comparison to traditional dark-colored EPDM or bituminous membranes, reflective cool membranes on low-slope roofs can reduce roof surface temperatures by as much as 45 to 70 degrees Fahrenheit (25° to 40°C) and cut building cooling costs by an estimated 15 to 25 percent. Cool roofing materials on steep roofs have the potential to save an estimated 5 to 10 percent of building cooling costs.

Cool color roofing materials are nonwhite in color but nevertheless reflect a significant portion of the sun's radiation. Cool colors are formulated with pigments that are selectively reflective to different portions of the solar spectrum. They are highly reflective of *near-infrared (NIR) radiation*, an invisible component of solar radiation that accounts for more than half of the total heat energy radiated by the sun, while they remain selectively absorptive in the visible light spectrum, which accounts for their perceived color. Cool color pigments can be applied to aggregate granules used to coat asphalt shingles, as well as to sheet metal, clay or concrete tile, fiber-cement shingles, and other roofing materials to produce products meeting cool roof standards for steep roofs.

	EPA Energy Star	USGBC LEED
Low-Slope Roofs	Minimum solar reflectance 0.65 unaged 0.50 aged 3 years	Minimum SRI 82 unaged 64 aged 3 years
Steep Roofs	Minimum solar reflectance 0.25 unaged 0.15 aged 3 years	Minimum SRI 39 unaged 32 aged 3 years

FIGURE 17.51
Cool roof requirements for low-slope and steep roofs. Both Energy Star and LEED specify values for new and aged materials. Aged values are based on membrane samples that have undergone accelerated weathering in the laboratory. These values are lower because the aging process reduces the roof covering's reflective and emittive effectiveness.

	Solar Reflectance	Thermal Emissivity	Solar Reflective Index (SRI)	Approximate Roof Surface Temperature Rise
Low-Slope Roofing				
White single-ply	0.90	0.85	115	10°F (5°C)
Bituminous membrane with reflective white-coated granules	0.75	0.90	90	20°F (10°C)
Bituminous membrane with light granules	0.35	0.90	35	55°F (30°C)
Black EPDM	0.10	0.85	5	80°F (45°C)
Steep Roofing				
Metal panel with cool white coating	0.70	0.85	85	25°F (15°C)
Metal panel with various color coatings	0.15–0.65	0.20–0.85	10–75	
Asphalt shingle with various color granulated surfaces	0.20–0.41	0.85–0.95	15–45	
Black asphalt shingle	0.05	0.90	0	90°F (50°C)

FIGURE 17.52
Approximate solar heating properties for selected roof materials. Only unaged values are shown. Materials in shaded rows cannot meet the cool roof criteria in Figure 17.51.

Dissimilar Metals and Galvanic Corrosion

When different metals come into contact with the presence of moisture, an electric current (flow of electrons) passes between them. Such metal pairs, or *galvanic couples*, form the basis, for example, for the storage of electrical energy in batteries. In building construction, galvanic couples are important for the manner in which the exchange of electrons affects the corrosion rates of the metals involved—a phenomenon that, if applied properly, can be used to positive effect or, if ignored, can lead to the premature deterioration of building components.

The Galvanic Series

In any galvanic couple, the metal donating electrons, called the *anode*, experiences an accelerated rate of corrosion; conversely, the metal receiving electrons, the *cathode*, experiences corrosion at a reduced rate. This effect is relatively great for pairs of metals with large differences between their electrochemical potentials and proportionally smaller for those with lesser potential difference.

To help predict the corrosion potential of metal pairs, metals may be listed in a *galvanic series*, that is, in order of their relative electrochemical potential, with the most anodic metals at one end of the list and the most cathodic ones at the other. Metal pairs positioned far apart in the series have greater corrosion potential than pairs closer to each other. Any number of galvanic series can be compiled for a group of metals in different conducting mediums. For building construction, a galvanic series based on metals immersed in flowing seawater is used (Figure A).

Applying the Galvanic Series to Problems in Building Construction

Corrosion in the Anode and the Cathode

A common application of galvanic couples is in the use of anodic metals as protective coatings for other cathodic metals. For example, consider *galvanized* (zinc-coated) *steel* fasteners. Zinc appears higher in the galvanic series and is therefore the anode in this pair of metals. Even if the zinc coating is damaged and the steel becomes exposed to moisture and air, the steel will remain protected. As long as there is sufficient surrounding zinc to sustain galvanic action between the metals, only the zinc will corrode, in effect sacrificing itself to preserve the steel. For the same reason, zinc and zinc-aluminum alloys are frequently applied as protective metallic coatings to steel sheet used for roofing and flashing. These alloys form sacrificial, protective coatings for the underlying steel.

Environmental Conditions

Galvanic pairs exposed to marine, salt-laden air or to atmospheres laden with industrial pollutants will undergo corrosion at a faster rate than others in less aggressive or more protected environments. For this reason, the more severe the environment, the more important it is to avoid detrimental contact between dissimilar metals. Or, where dissimilar metals are combined in such environments, only metal pairs with small electrical potential difference should be considered. In more benign exterior environments, or within the building interior, metal pairs with greater potential difference will perform acceptably.

Relative Surface Area of Anode to Cathode

The corrosive effects within a galvanic couple are proportional to the relative surface areas of the metals involved. For example, consider copper roofing fastened with stainless steel fasteners. In this metal pair, copper is the anode and at risk of corrosion. However, the relative surface area of anode to cathode is large. That is, the surface area of the copper roofing is large in relation to the surface area of the stainless steel fasteners. This means that the electrochemical effects are diluted over a very large area of the copper and remain relatively benign. In fact, the use of stainless steel fasteners for the attachment of most types of metal roofing, including copper, is quite common. In contrast, consider the use of galvanized steel fasteners for the attachment of copper roofing. In this case, the fasteners are the anode in the galvanic couple, and the ratio of surface area of anode (fastener) to cathode (roof metal) is very low. This condition will lead to rapid corrosion of the fasteners.

Water Flowing from One Metal to Another

Where rainwater flows from one metal type to another, the first metal should be anodic in relation to the second. Consider again a copper roof, in this case draining into a stainless steel gutter. As rainwater washes off the roof metal, it will carry dissolved copper ions into the gutter. Because the stainless steel is cathodic in relation to the copper, the gutter metal itself will remain unharmed. Conversely, consider the same roof with a galvanized steel gutter. In this case, the galvanized steel gutter metal is anodic in relation to the dissolved copper washing through it and will experience accelerated corrosion.

Insulating Dissimilar Metals

For galvanic action to occur, electric current must flow between the metals. By insulating dissimilar metals from each other, corrosion can be prevented. For example, a layer of felt paper or rubberized asphalt membrane may be used to separate dissimilar sheet metal materials used in roofing and flashing work.

Paints, aluminum anodizing, and other coatings can also act as insulators between one metal and another. However, when using coatings to separate dissimilar metals, coating only the surface of the anodic metal should be avoided. In this scenario, small failures in the coating can expose small areas of anodic metal, creating very low anode to cathode area ratios and accelerating corrosion in those areas. Instead either the surface of the cathodic metal, or both surfaces, should be coated.

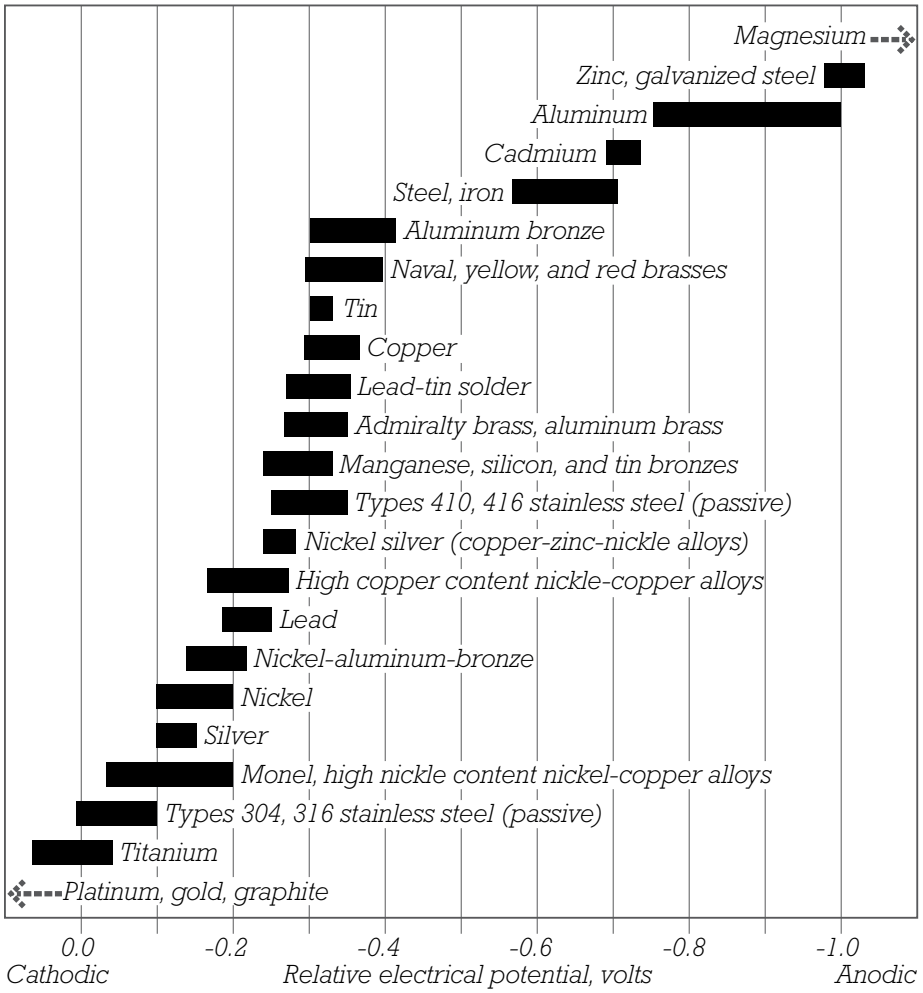


Figure A

The galvanic series for selected metals, immersed in flowing seawater, adapted from ASTM G82. When paired as galvanic couples, metals positioned toward the right will sacrificially corrode while protecting metals positioned toward the left. As a rule of thumb, metals with a potential difference of less than 0.1 to 0.2 volts experience little galvanic corrosion, except in severe environments. The stainless steel alloys in the chart can appear in different locations within the series, depending on their chemical state and the environment to which they are exposed. In this series, stainless steels are listed in what is called their passive states, their condition under normal usage.

Green Roofs

Green roofs, also called *vegetated roofs*, are roofing systems covered with vegetation, soil, and other materials needed to support plant growth. Like protected membrane roofs, green roofs extend the life of the roof membrane by shielding it from UV radiation and extremes of temperature. Green roofs may reduce building heating and cooling costs by moderating temperature swings in the roof assembly. They reduce the transmission of noise through the roof system, lessen the intensity of stormwater runoff from the roof, and provide habitat for birds and insects. By supporting plant growth and reducing heat island effects, green roofs improve air quality. Green roofs are attractive, and they can provide pleasant roofscape spaces for building occupants.

Extensive green roofs are relatively shallow, with soil depths of 2 to 6 inches (25 to 150 mm). They are planted with herbs, grasses, mosses, sedums, or other drought-tolerant plants that do not require irrigation or frequent maintenance (Figures 17.53 and 17.54). *Intensive green roofs* may have soils as deep as 30 inches (750 mm) and are designed to support a broader variety of plant types and shrubs. Intensive roofs require irrigation and regular maintenance such as weeding, trimming, pest management, and fertilization.

The structure supporting a green roof must be designed to support the added weight of plant materials, soil, and water retained within the roof system. Because of their lesser depth, extensive roofs are relatively light in weight, imposing loads, when saturated with water, ranging from 12 to 35 psf (0.57 to 1.7 kPa) on the supporting roof structure. Intensive roofs can impose loads of 50 psf (2.4 kPa) or more. Although most green roofs are essentially flat, extensive roofs with slopes as great as 12:12 (1 in 1) are feasible with special soil retention measures.

From the top down, typical components of a green roof system include:

- **Plant materials** may be selected on the basis of hardiness, climate, depth of soil, maintenance expectations, and appearance.
- The **growth medium** (soil) must provide long-lasting, healthy growing conditions. Its formulation varies with the depth of soil, the types of vegetation supported, and other considerations.

Figure 17.53
A green roof over a sloping roof deck. This extensive planted roof has a 6-inch (150-mm)-deep soil layer and supports native and ornamental grasses. (*Design by John Senhauser Architects, courtesy of Steve Grim.*)

Interactive Exercise

- A geotextile **filter fabric** prevents soil particles from washing out of the growth medium and clogging the drainage layer below.
- **Soil restraints** made from perforated plastic or metal allow the free flow of water while confining the growth medium at the roof perimeter and around drains or scuppers.
- **Drainage layer** materials, such as a molded plastic panel or an entangled plastic filament mat, provide efficient drainage and aeration beneath the soil. Some products also provide **water retention**, benefiting the plants' subsoil environment.
- Rigid foam **insulation** boards may be positioned above or below the roof membrane. Insulation boards must be sufficiently strong in compression to resist the weight of the soil and plant materials above.
- Depending on the membrane system, one or more **protection layers** to prevent root invasion or physical damage may be laid over the membrane.
- Because access to the **waterproofing membrane** becomes difficult once it is covered with the green roof components, the membrane should be chosen with consideration of its long-term performance in a buried, continuously damp environment. Especially for intensive green roofs, robust waterproofing systems are preferred over lighter-duty, conventional roof membranes.
- Requirements for the **vapor retarder** and **air barrier** are no different for green roofs than for conventional low-slope roof assemblies.
- The **roof deck** and **supporting structure** must be engineered to carry the additional loads imposed by green roof components.

With *modular green roof systems*, the components of the green roof system above the membrane are preassembled in easily transported and assembled tray-like modules. These trays, typically 2 to 4 feet (600 to 1200 mm) in plan dimension and 2 to 8 inches (50 to 200 mm) in depth, are preplanted and arrive on the construction site ready to be placed over the roof membrane. Modular green roof systems are relatively lightweight, easy to specify, easy to assemble on site, and easy to remove or adjust at a later date.

FIGURE 17.54
Built on a steep slope, the roofs of the building below have a strong presence in the landscape and view beyond. Plantings on the green roof integrate with the terraced landscaping in the foreground while the standing-seam sheet metal contrasts with the body of water beyond. *(Photo by Joseph Iano.)*

FIGURE 17.55
A rooftop-mounted array of photovoltaic modules. Each module is composed of a series of round tubes coated with thin-film PV material. The PV tubes convert light coming from any direction, such as directly from the sun, from the diffuse sky on cloudy days, or reflected back from the reflective white roof membrane. This array, situated in the relatively cloudy Pacific Northwest, covers 2.5 acres of roof area and is capable of generating more than 830,000 kWh of electricity annually. *(Photo by Joseph Iano.)*

PHOTOVOLTAIC SYSTEMS

Photovoltaic (*PV*) materials directly convert sunlight to electricity. Traditional first-generation photovoltaic systems rely on semiconducting crystalline silicon for this conversion process. Thin wafers or cells of this material are assembled to make *PV modules*, also called *solar panels*. Collections of such modules, called *PV arrays*, are mounted to the roof (or exterior walls) of a building and interconnected to produce direct-current electricity.

Second-generation *thin-film PV* materials are made from amorphous silicon (a noncrystalline form of silicon) or other semiconducting materials. They can be applied in thin, flexible layers over many other materials (Figure 17.55). Thin-film PVs are less expensive than crystalline silicon, but also less efficient at converting sunlight to electricity. They are especially well suited to *building-integrated photovoltaics* (*BIPVs*), in which they are laminated onto conventional cladding, roofing, and glazing components and made part of the fabric of the building enclosure.

Emerging third-generation PV materials, also produced in thin films, are made from a diverse range of organic and inorganic materials. They are inexpensive to manufacture and are expected to achieve conversion efficiencies similar to those of second generation PVs. They also open up new possibilities in color range and transparency.

FIGURE 17.56
A house is both roofed and sided with red cedar shingles to feature its sculptural qualities. *(Architect: William Isley. Photo by Paul Harper, courtesy of Red Cedar Shingle and Handsplit Shake Bureau.)*

Electricity produced by any type of PV array is fed through equipment that regulates and converts the direct-current output to alternating current at typical building power voltages. Where permitted by the public utility, this power may be sold back into the utility grid and used to offset power consumption charges. Or, in a *stand-alone* (*off-grid*) *PV system*, PV power is fed into rechargeable batteries or some other type of storage system, and then drawn for use on demand.

MasterFormat Sections for Roofing

07 22 00	**ROOF AND DECK INSULATION**
07 31 00	**SHINGLES AND SHAKES**
07 31 13	Asphalt Shingles
07 31 16	Metal Shingles
07 31 19	Mineral-Fiber Cement Shingles
07 31 26	Slate Shingles
07 31 29	Wood Shingles and Shakes
07 31 33	Composite Rubber Shingles
07 31 53	Plastic Shingles
07 32 00	**ROOF TILES**
07 32 13	Clay Roof Tiles
07 32 16	Concrete Roof Tiles
07 33 00	**NATURAL ROOF COVERINGS**
07 33 16	Thatched Roofing
07 33 63	Vegetated Roofing
07 41 00	**ROOF PANELS**
07 41 13	Metal Roof Panels
07 51 00	**BUILT-UP BITUMINOUS ROOFING**
07 52 00	**MODIFIED BITUMINOUS MEMBRANE ROOFING**
07 53 00	**ELASTOMERIC MEMBRANE ROOFING**
07 53 29	Ethylene-Propylene-Diene-Monomer Roofing
07 54 00	**THERMOPLASTIC MEMBRANE ROOFING**
07 54 19	Polyvinyl-Chloride Roofing
07 54 23	Thermoplastic-Polyolefin Roofing
07 55 00	**PROTECTED MEMBRANE ROOFING**
07 56 00	**FLUID-APPLIED ROOFING**
07 58 00	**ROLL ROOFING**
07 61 00	**SHEET METAL ROOFING**
07 61 13	Standing Seam Sheet Metal Roofing
07 61 16	Batten Seam Sheet Metal Roofing
07 61 18	Flat Seam Sheet Metal Roofing
07 62 00	**SHEET METAL FLASHING AND TRIM**
07 71 00	**ROOF SPECIALTIES**
07 71 13	Manufactured Copings
07 72 00	**ROOF ACCESSORIES**
07 72 23	Relief Vents
07 72 26	Ridge Vents
07 76 00	**ROOF PAVERS**

Roofing and the Building Codes

For most roofing materials, minimum requirements for manufacturing standards, slopes, underlayment materials, and installation are specified by building codes. Codes also regulate a roof's required level of resistance to flame spread and fire penetration, tested according to standards ASTM E108 or UL 790 and rated as *Class A*, *B*, or *C roof coverings*. (Class A rated roofs are the most fire-resistant, and unclassified roofs, the least resistant.)

In the International Building Code, most roofs must meet Class B or C requirements, depending on the building construction type. (See Chapter 1 for more information about construction types.) Most roofs for single-family homes and other building types regulated by the International Residential Code may remain unclassified. However, when building in areas with a high risk of wildfire, a rating as high as Class A may be required.

Roof class ratings are based on the testing of whole roof assemblies, including the membrane, shingles or other covering, underlayments, insulation, decking, and even ballast, if any. Most low-slope membrane roof systems can meet a Class A rating, as can many roofs covered with noncombustible materials such as sheet metal, or concrete or clay tiles. Roofs covered with asphalt shingles can meet Class A or B requirements, depending on the shingle composition. And roofs covered with fire-retardant wood shingles and shakes can meet Class C requirements.

Key Terms

slope, pitch
rise
run
low-slope roof
roof deck
thermal insulation
air barrier
vapor retarder
roof membrane
drainage component
roof flashing
ponding
substrate board
area divider
compact insulated roof
protected membrane roof (PMR)
ballastinsulation coverboard
lightweight insulating concrete
vented metal roof decking
multi-ply bituminous roof membrane
built-up roof (BUR) membrane
cold-applied mastic
modified bitumen roof membrane
atactic polypropylene (APP)
styrene-butadiene-styrene (SBS)
torch-applied modified bitumen membrane
hot-mopped modified bitumen membrane
cold process modified bitumen membrane, cold-applied adhesive modified bitumen membrane
self-adhered modified bitumen membrane
cap sheet
hybrid membrane bituminous roof
single-ply roof membrane
thermoplastic material
thermosetting material
polyvinyl chloride (PVC)
thermoplastic polyolefin (TPO)
ketone ethylene ester (KEE)
ethylene propylene diene monomer (EPDM)
fluid-applied roof membrane
traffic deck
sheet metal flashing
membrane flashing
strip flashing (stripping)
fascia
scupper
base flashing
parapet
counterflashing
coping
roof drain
roof penetration
cant strip
structural metal panel roofing
purlin
steep roof
thatch
shingle
wood shingle
wood shake
skip sheathing, spaced sheathing
breather mat
asphalt shingle, composition shingle
valley
open valley
woven valley
cut valley
roll roofing
slate shingle
clay tile
concrete tile
architectural sheet metal roofing
oil canning
standing-seam metal roofing
flat-seam metal roofing
batten-seam metal roofing
lead
copper
zinc
stainless steel
titanium
zinc-tin alloy coated stainless steel
terne-coated stainless steel
patina
aluminum
metallic-coated steel
zinc-tin alloy coated steel
ferrous steel
gauge, gage
galvanic corrosion
galvanic couple
anode
cathode
galvanic series
galvanized steel
cool roof
solar reflectance, albedo
thermal emittance
solar reflective index (SRI)
cool color
near-infrared (NIR) radiation
green roof, vegetated roof
extensive green roof
intensive green roof
modular green roof system
photovoltaic (PV) material
PV module, solar panel
PV array
thin-film PV
building-integrated photovoltaics (BIPVs)
stand-alone PV system, off-grid PV system
Class A, B, C roof coverings

Review Questions

1. What is the difference between a low-slope roof and a steep roof? What are the advantages and disadvantages of each type?

2. Discuss the positions in which thermal insulation may be installed in a low-slope roof, and the advantages and disadvantages of each.

3. Compare a multi-ply bituminous roof membrane to a single-ply roof membrane.

4. What is the difference between cedar shingles and cedar shakes?

5. What metals are used for architectural sheet metal roofing? What are the strengths and drawbacks of each?

6. What are the benefits of a cool roof? What properties of a roofing material affect its solar heating and how?

7. List the major components of a green roof system and describe their functions.

Exercises

1. For a low-slope-roofed university classroom building with a masonry bearing wall, steel interior frame, corrugated steel roof deck, and parapet:

   a. Show two ways of achieving a 1:50 roof slope on structural bays 36 feet (11 m) square.

   b. Sketch a set of details of the parapet edge, building separation joint, area divider, and roof drain for a low-slope roof system of your choice. Show insulation, vapor retarder (if any), roof membrane, and flashings.

2. Sketch a fascia detail for a low-slope roof system of your choice, assuming that the wall below is made of precast concrete panels and the roof deck of precast concrete slab elements.

3. Find a low-slope roof system being installed and take notes on the process until the roof is completed. Ask questions of the roofers, the architect, or your instructor about anything you don't understand.

4. Examine a number of low-slope roofs around your campus or neighborhood, looking for problems such as cracking, blistering, tearing, and leaking. Attempt to explain the reasons for each problem that you discover.

Selected References

National Roofing Contractors Association. *The NRCA Roofing Manual: Steep-Slope Roof Systems; The NRCA Roofing Manual: Architectural Metal Flashing, Condensation Control and Reroofing; The NRCA Roofing Manual: Membrane Roof Systems; The NRCA Roofing Manual: Metal Panel and SPF Roof Systems.* Rosemont, IL, updated regularly.

These manuals, all updated regularly, are the most comprehensive guides to current U.S. practice for low-slope and steep-slope roofing systems. The treatment is exhaustive, and both diagrams and text are excellent. These products may also be available in combined editions.

Sheet Metal and Air Conditioning Contractors National Association. *Architectural Sheet Metal.* Chantilly, VA, updated regularly.

Architectural sheet metal roofs are copiously detailed in this excellent reference, along with every conceivable flashing, fascia, gravel stop, and gutter for flat and shingled roofs.

Zahner, L. William. *Architectural Metals: A Guide to Selection, Specification, and Performance* (3rd ed.). Hoboken, NJ, John Wiley & Sons, 1995.

A comprehensive treatment of architectural metal types and their uses in construction.

Websites

Roofing

Asphalt Roofing Manufacturers Association: www.asphaltroofing.org

Cool Metal Roofing Coalition: www.coolmetalroofing.org

Cool Roof Rating Council: www.coolroofs.org

Whole Building Design Guide, Roofing Systems: www.wbdg.org/guides-specifications/building-envelope-design-guide/roofing-systems

Low-Slope Roofs

Carlisle SynTec: www.carlisle-syntec.com

Firestone Building Products: www.firestonebpco.com

National Roofing Contractors Association: www.nrca.net

Polyisocyanurate Insulation Manufacturers Association: www.polyiso.org

Steep Roofs

Cedar Shingle and Shake Bureau: www.cedarbureau.org

CertainTeed (roofing products): www.certainteed.com

Copper Development Association: www.copper.org

GAF (roofing products): www.gaf.com

Metal Construction Association: www.metalconstruction.org

Sheet Metal and Air Conditioning Contractors' National Association: www.smacna.org

Umicore Building Products (zinc roofing): www.vmzinc-us.com

18

Glass and Glazing

- **History**
- **The Material Glass**
  - Annealed Glass
  - Heat-Treated Glass

Sustainability and Glass

  - Laminated Glass
  - Safety Glazing
  - Fire-Rated Glass
  - Glass That Protects against Fading
  - Fritted and Spandrel Glass
  - Tinted and Reflective Coated Glass
  - Insulating Glass
  - Low-Emissivity Coated Glass
  - Glass for Structural Use

Other Types of Glass

  - Plastic Glazing
- **Glazing**
  - Glazing Small Lites
  - Glazing Large Lites
  - Advanced Glazing Systems
- **Glass and Energy**
- **Glass and the Building Codes**

Case Study: Skating Rink at Yerba Buena Gardens

A spiral glass staircase designed by Eckersley O'Callaghan and Bohlin Cywinski Jackson. The stair is made entirely of laminated glass with titanium point-supported fittings. *(Photo by Joseph Iano.)*

Glass plays many roles and takes many forms in buildings: Gothic church windows made of thousands of jewel-like pieces of colored glass; breathtaking expanses of smooth, uninterrupted glass that fill whole walls of modern buildings; Elizabethan casement windows with tiny diamond panes set in lead; skyscrapers that shimmer in facets, mirroring the sky; cozy windows; comfortable windows; windows that bring soft, natural light; windows that frame spectacular views; windows that welcome winter sunlight to warm a room; windows that dissolve the boundaries between inside and outside. But glass can also form windows that make privacy impossible; windows that admit a harsh, glaring light; winter-cold surfaces that chill the body and tax the heating system; windows that broil a room in summer afternoon sunlight. Glass skillfully used in building contributes to more efficient, comfortable, and joyful architecture. But thoughtlessly used, glass can make a building unattractive, uneconomical, and uncomfortable to inhabit.

History

The origins of glass are lost in prehistory. Initially a material for colored beads and small bottles, glass was first used in windows in Roman times. The largest known piece of Roman glass, a crudely cast sheet used for a window in a public bath at Pompeii, was nearly 3 × 4 feet (800 × 1100 mm) in size.

By the 10th century, the Venetian island of Murano had become the major center of glassmaking, producing *crown glass* and *cylinder glass* for windows. Both the crown and cylinder processes began by blowing a large glass sphere. In the crown process, the heated glass sphere was adhered to an iron rod called a *punty* opposite the blowpipe. The blowpipe was then removed, leaving a hole opposite the punty. Next, the sphere was reheated, whereupon the glassworker spun the punty rapidly, causing centrifugal force to open the sphere into a large disk, or crown, 30 inches (750 mm) or more in diameter (Figure 18.1). When the crown was cut into panes, one pane always contained the "bullseye" where the punty had been attached before being cracked off. In the cylinder process, the sphere, heated to a molten state, was swung back and forth, pendulum fashion, on the end of the blowpipe to elongate it into a cylinder. The hemispherical ends were cut off, and the remaining cylinder was slit lengthwise, reheated, opened, and flattened into a rectangular sheet of glass that was later cut into panes of any desired size (Figure 18.2). Before the introduction of modern glassmaking techniques, crown glass was favored over cylinder glass for its surface finish, which was smooth and brilliant because it was formed without contacting another material. Cylinder glass, though more economical to produce, was limited in surface quality by the texture and cleanliness of the surface on which it was flattened.

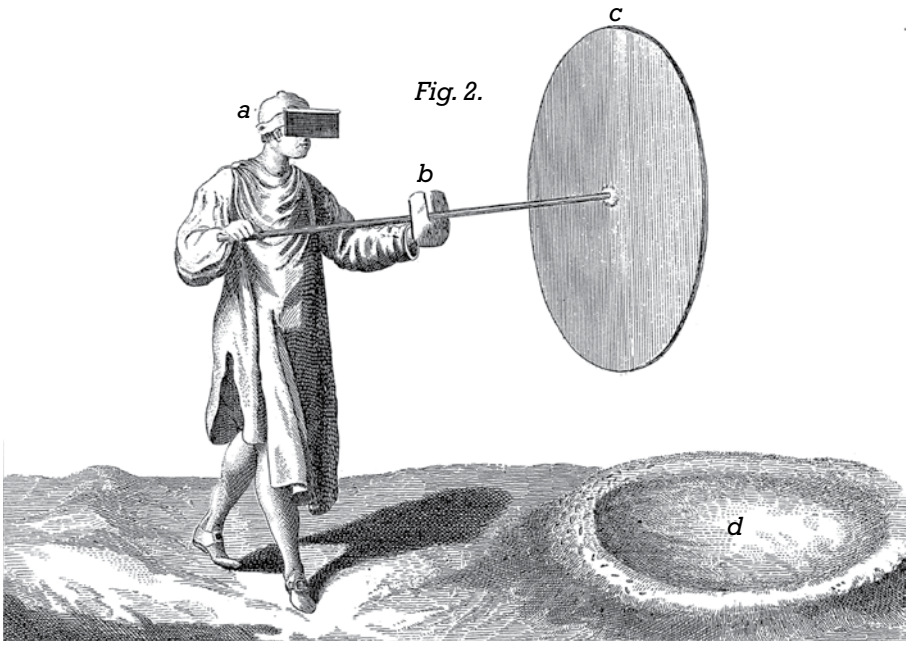


Figure 18.1
The glassworker in this old engraving wears a face shield (*a*) and hand shield (*b*) to protect against the heat of the large glass crown (*c*) that he has just spun on the end of a punty. After cooling, the crown is cut into small lites of window glass. *(Courtesy of the Corning Museum of Glass, Corning, NY.)*

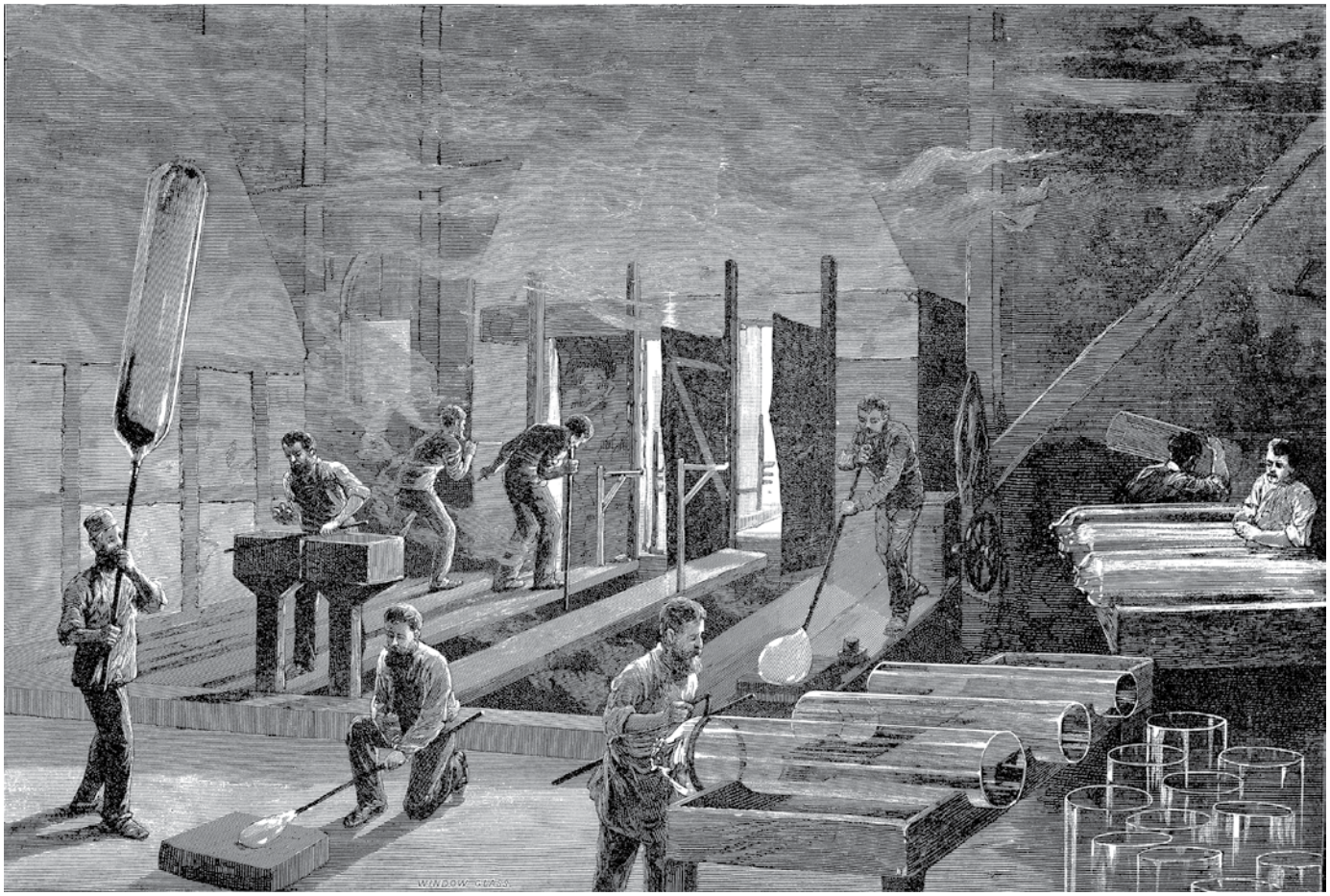


Figure 18.2
Making cylinder glass in the 19th century, Pittsburgh, Pennsylvania. Elongated glass bottles are blown by swinging the blowpipe back and forth in the pit in front of the furnace (*center*). As each bottle solidifies (*left*), it is brought to another area where the ends are cut off to produce cylinders (*right*). The cylinders are reheated and flattened into sheets from which window glass is cut. *(Courtesy of the Corning Museum of Glass, Corning, NY.)*

Neither crown glass nor cylinder glass was of sufficient optical quality for the fine mirrors desired by the 17th-century nobility. For this reason, *plate glass* was first produced, in France, in the late 17th century. Molten glass was cast into frames, spread into sheets by rollers, cooled, then ground flat and polished with abrasives, first on one side and then the other. The result was a costly glass of near-perfect optical quality in sheets of unprecedentedly large size. Mechanization of the grinding and polishing operations in the 19th century reduced the price of plate glass to a level that allowed it to be used for storefronts in both Europe and America.

In the 19th century, the cylinder process evolved into a method of drawing cylinders of molten glass vertically from a crucible. This made possible the routine, economical production of cylinders 40 to 50 feet (12 to 15 m) long. In 1851, the Crystal Palace in London (Figure 11.1) was glazed with 900,000 square feet (84,000 m^2) of cylinder glass supported on a cast iron frame.

In the early years of the 20th century, cylinder glass production was gradually replaced by processes that pulled flat sheets of *drawn glass* directly from a container of molten glass. Highly mechanized production lines for the grinding and polishing of plate glass were established, with rough glass sheets entering the line continuously at one end and finished sheets emerging at the other.

In 1959, the English firm of Pilkington Brothers Ltd. started production of *float glass*, which has since been licensed to other glassmakers and has become the worldwide standard, replacing both drawn glass and plate glass. In this process,

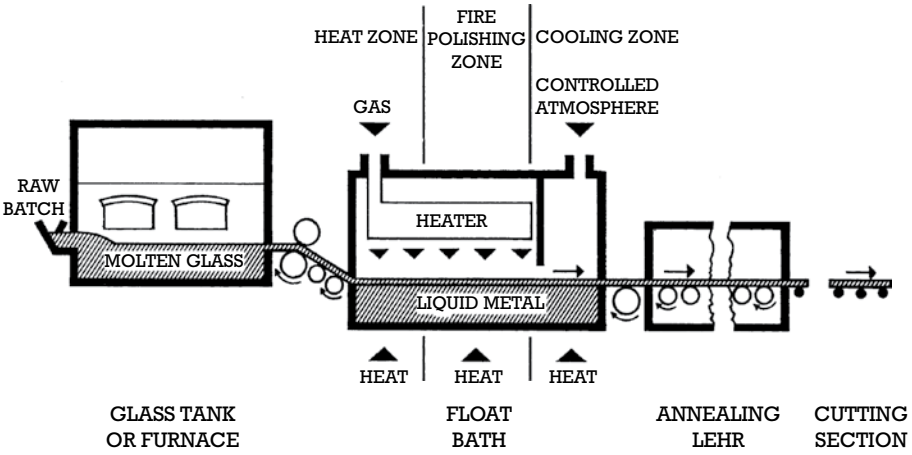


FIGURE 18.3
In the float glass process, molten glass from the furnace is floated on a bath of liquid tin to form a continuous sheet of glass. The annealing *lehr* cools the glass at a controlled rate to avoid internal stresses, after which it is cut into smaller sheets. *(Courtesy of PPG Industries.)*

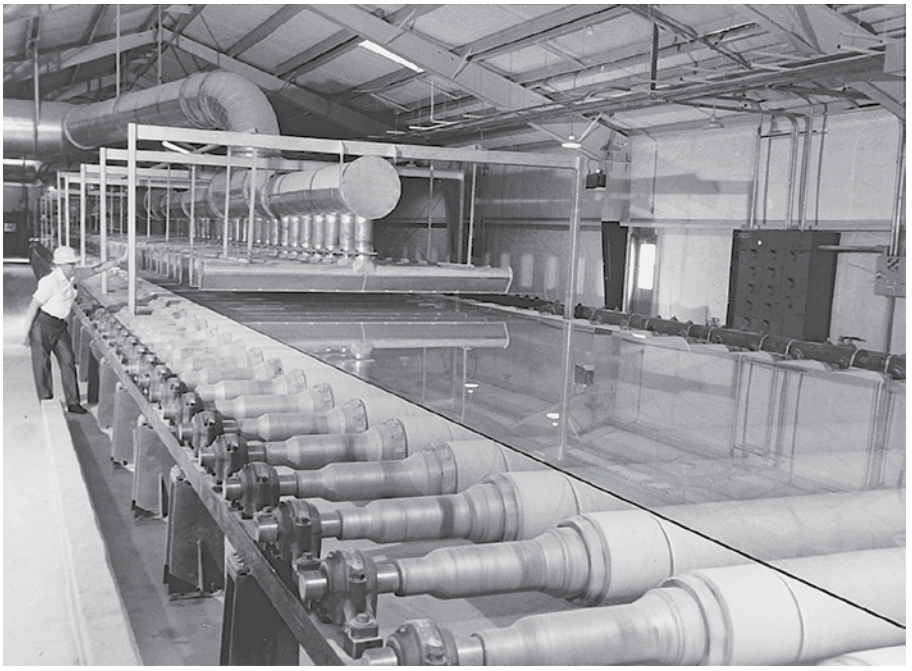


FIGURE 18.4
The superior flatness and bright surface finish of float glass are readily seen in the reflections on the glass ribbon emerging from the annealing lehr. *(Courtesy of the Libbey-Owens-Ford (LOF) Company.)*

a ribbon of molten glass is floated across a bath of molten tin, where it hardens before touching a solid surface (Figures 18.3, 18.4, and 18.5). The resulting sheets of glass have parallel surfaces, high optical quality (virtually indistinguishable from that of plate glass), and a brilliant surface finish. Nearly all glass used in buildings is now produced as float glass. Float glass has been produced in North America since 1963 and now accounts for nearly all domestic flat glass production. (The term *flat glass* refers to glass manufactured in flat sheets, used primarily for architectural and automobile applications, as distinct from other glass types with different chemical makeups used in the manufacturer of, for example, glass containers, glass reinforcing fibers, or optical communications fibers.)

The terminology associated with glass developed early in this long history. The term *glazing* as it applies to building can refer either to the installation of glass in an opening or to the material itself (usually glass, but also plastic or other transparent or translucent material) in a glazed opening. The installer of glass is known as a *glazier*. Individual pieces of glass are known as *lights*, or often, to avoid confusion with visible light, *lites*.

Figure 18.5
Track-mounted cutting devices score the ribbon of cooled float glass as part of a computer-controlled cutting operation that automatically produces the glass sizes ordered by customers. *(Courtesy of PPG Industries.)*

The Material Glass

The major ingredient of glass is sand (silicon dioxide). Sand is mixed with soda ash (sodium hydroxide or sodium carbonate), lime, and small amounts of alumina, potassium oxide, and other elements to control color, then heated to form glass. The finished material, while seemingly crystalline and rigid, is actually an amorphous solid, with no fixed melting point and an open, noncrystalline microstructure.

When drawn into small fibers, glass is stronger than steel, though not nearly as stiff. In larger pieces, the microscopic imperfections that are an inherent characteristic of glass reduce its useful strength to significantly lower levels, particularly in tension. When a surface of a sheet of glass is placed in sufficient tension, as happens when an object strikes the glass, cracks propagate from an imperfection near the point of maximum tension and the glass shatters.

Annealed Glass

During its manufacture, ordinary flat glass is *annealed*, meaning that it is cooled slowly to prevent locking in thermal stresses that can cause unpredictable behavior when the glass is put in use. ASTM C1036 defines the basic characteristics of flat annealed glass, such as its dimensional tolerances, visual quality, and classifications of use. Traditionally, glass thickness is described in fractional inches, while the current standard refers to nominal (rounded) metric units. At this time, both methods of description remain in use (Figure 18.6).

Heat-Treated Glass

Heat-treated glass is produced by reheating annealed glass in an oven to approximately 1200 degrees Fahrenheit (650°C) and then cooling both of its surfaces rapidly (*quenching*) with blasts of air while its core cools more slowly. This process induces permanent compressive stresses in the edges and faces of the glass and tensile stresses in the core. The resulting glass is stronger in bending than annealed glass and more resistant to thermal stress and impact. These properties make heat-treated glass useful for windows exposed to heavy wind pressures, impact, or intense heat or cold. By adjusting the quenching process, greater or lesser degrees of prestress may be introduced into the glass, producing products referred to as either tempered glass or heat-strengthened glass.

Tempered Glass

In *tempered glass*, the induced compressive stresses are at least 10,000 psi (69 MPa), resulting in glass that

Sustainability and Glass

Glass is inert, chemical-resistant, and easy to keep clean. If not broken, it can last as long as the building within which it is installed, without loss of quality. Glass manufacture is energy- and capital-intensive.

Energy Performance

Glass has a large impact on energy consumption and the interior environment of a building, and can be beneficial or detrimental depending on how it is used. Poorly used, glass contributes to excessive energy losses, visual glare, and occupant discomfort. When used well, it can save energy, bring daylight into the building interior, and improve occupant well-being and productivity.

Building and Material Life-Cycle Impacts

- Flat glass accounts for less than 1 percent of construction demolition waste. It is easily down-cycled into aggregate for earth fill or for use in concrete, abrasives, roofing shingles, ceramic tiles, sports surfaces, and filtration media. In order to be recycled into new flat glass, it must be carefully demolished and processed to avoid contamination, a process that is labor intensive and expensive.
- Polycarbonates are 100 percent recyclable.
- ETFE is 100 percent recyclable.
- A glass manufacturer EPD reports the following cradle-to-gate impacts per metric tonne (2200 lb) of architectural flat glass:

Nonrenewable primary energy consumption	20,000 MJ (19 million BTU)
Global warming potential	720 kg (1600 lb) CO_2 eq.
Fresh water consumption	1100 m^3 (290,000 gal)

- Foreseeable improvements in furnace technology and waste heat recovery afford the possibility of reductions in energy consumption in the range of 20 to 25 percent.
- Glass manufacture involves the release of significant quantities of combustion byproducts and particulates. There is little solid waste generated.
- Large volumes of water are used during the cooling and cleaning phases of glass production. But with care, this water can be recaptured and reused.

Material and Production Attributes

- One ton of new glass requires approximately 1200 pounds (5400 kg) of sand, 360 pounds (160 kg) of soda ash, 270 pounds (120 kg) of dolomite, and 170 pounds (77 kg) of other minerals and metals, all finite but abundant materials.
- 5 million tons (4.5 million tonnes) of flat glass are produced annually in the United States.
- The recycled content of architectural flat glass is in the range of 5 to 25 percent.
- Polycarbonates have up to 25 percent recycled content.

Unhealthful Materials and Emissions

- There are no recognized health hazards associated with the material glass.
- The manufacture of some special glass types involves the generation of unhealthful compounds, such as hydrogen chloride and hydrogen fluoride acids, arsenic, antimony, and selenium.
- Glass does not emit VOCs or other unhealthful compounds.

Metric Units	Inch-Pound	Common Applications
2.5 mm	3/32 in. (also called *single-strength*)	Mirrors, window glass, laminated glass
3 mm	1/8 in. (also called *double-strength*)	
6 mm	1/4 in.	
8 mm	5/16 in.	
10 mm	3/8 in.	Frameless glass doors, glass partitions, structural laminated glass
12 mm	1/2 in.	
19 mm	3/4 in.	Glass furniture
25 mm	1 in.	

Figure 18.6
Flat glass thickness designations and common applications.

is four times as strong in bending as annealed glass. If tempered glass does break, the sudden release of its internal stress reduces it almost instantaneously to small, square-edged granules rather than long, sharp-edged shards. This characteristic, combined with its high strength, qualifies it for use as safety glazing (discussed later in this section) in locations of possible occupant impact. Tempered glass is also used, for example, for glass railings and frameless, all-glass doors (Figure 18.7).

Tempered glass is more costly than annealed glass. It often has

FIGURE 18.7
Tempered glass is used for strength and breakage safety in both the doors and windows of this store in a downtown shopping mall. *(Photo by Edward Allen.)*

noticeable optical distortions created by the tempering process. All cutting to size, drilling, and shaping of edges must be done before the heat treatment of the glass, because any such operations after tempering will release the stresses in the glass and cause it to disintegrate. The high prestress in tempered glass also makes it more vulnerable to spontaneous breakage caused by either impurities within the glass or damage to its edges. Tempered glass is sometimes referred to as *fully tempered glass* to distinguish it more clearly from heat-strengthened glass.

Heat-Strengthened Glass

The induced stresses in *heat-strengthened glass* are about half as high as those in tempered glass. Heat-strengthened glass is about twice as strong in bending as annealed glass. It usually has fewer distortions than tempered glass, and cutting and other fabrication operations can be performed after it has been heat treated without its shattering. Its breakage behavior is more like that of annealed glass. For that reason, it cannot be used as safety glazing except in laminated form.

FIGURE 18.8
The entrance canopy of Newport Hospital in Rhode Island is made of laminated glass supported by stainless steel point-supported fittings. *(Architects: Taylor and Partners. Photo of Pilkington Planar system by W&W Glass Systems, Inc.)*

Laminated Glass

Laminated glass is made by sandwiching sheets of thin, transparent plastic film, called *interlayers*, between sheets of glass and bonding the glass and plastic together under heat and pressure. The main reason to laminate glass is to better control its breakage behavior. Laminated glass is not necessarily as strong as annealed glass of the same total thickness. But when laminated glass breaks, the resilient interlayer material holds the shards of glass in place rather than allowing them to fall out of the frame that holds them. In this way, laminated glass does not create dangerous, loose shards, and it can, like tempered glass, serve as safety glazing.

Polyvinyl butyral (*PVB*) is the most commonly used interlayer material. By varying the interlayer material thickness and the number of interlayers, and by heat-strengthening or tempering the glass itself, laminated units of varying strength can be produced. Other interlayer materials, such as ethylene vinyl acetate (EVA), polyester (PET), thermoplastic polyurethane (TPU), and ethylene/methacrylic acid copolymers (ionoplast), can be used to further increase the range of strength, toughness, durability, optical clarity, and other properties of laminated glass units.

In addition to safety glazing applications, laminated glass may be used in skylights and other overhead glazing, where it can prevent injury to people below from falling glass (Figures 18.8 and 18.9). Laminated glass is a better barrier to the transmission of sound than solid glass and is used to glaze windows of residences, classrooms, hospital rooms, and other spaces that must be kept quiet in the midst of noisy environments. Colored or patterned interlayers may be used to produce a wide range of visual effects in laminated glass.

Thicker laminated glass units are used in structural applications, such as glass floors and stair treads—these are discussed in more detail later in this section. Laminated glass is also used in applications requiring resistance to special types of impact, such as glazing resistant to windborne debris, forced entry, ballistics, or blasts. These are described in more detail in Chapter 19.

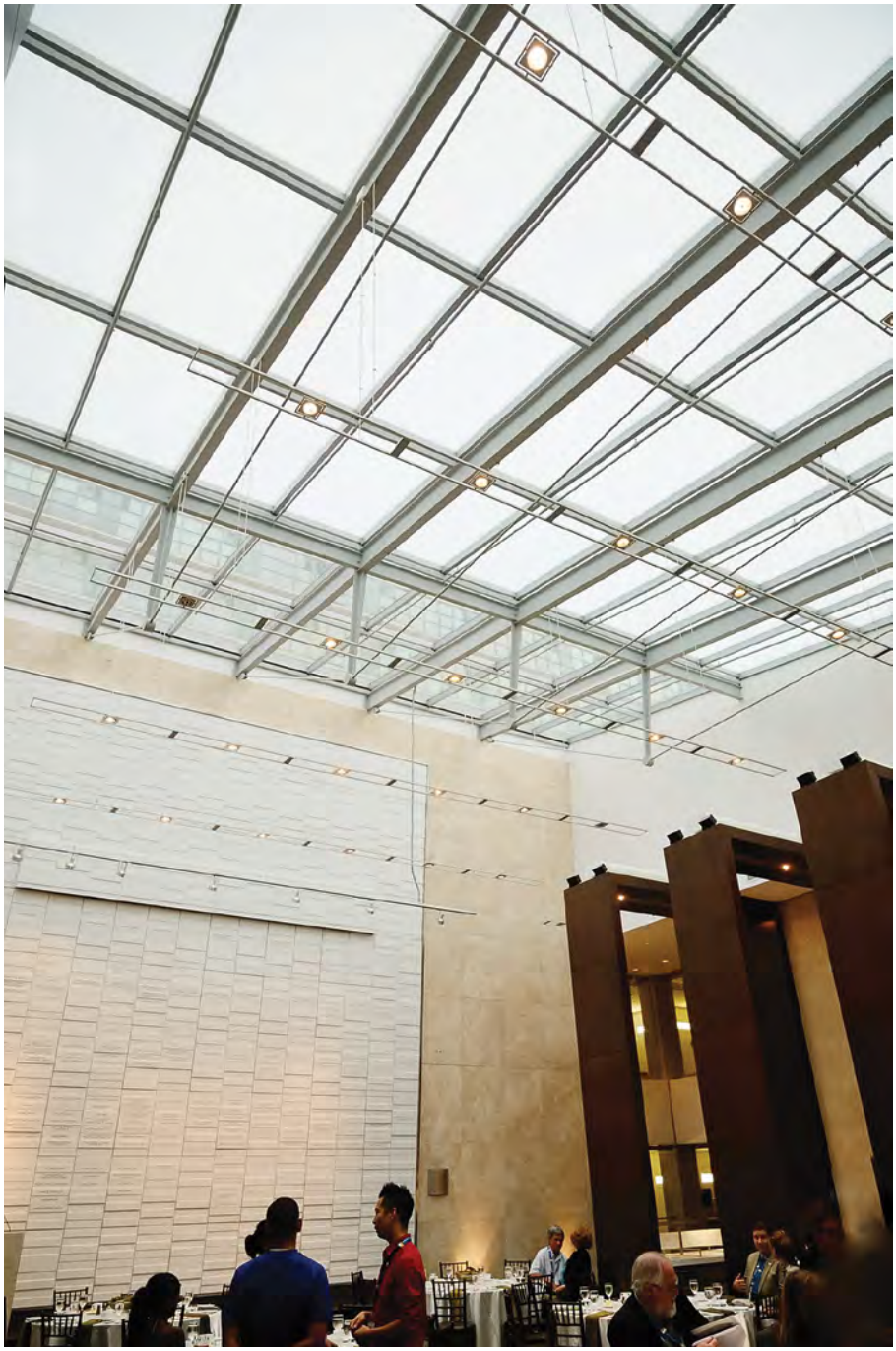


Figure 18.9
Laminated glass provides safety against falling shards in an overhead glazing installation. *(Photo by Joseph Iano.)*

Safety Glazing

Glass and other transparent glazing materials installed where they could be subject to human impact must meet requirements for *safety glazing*. This means that the material must be resistant to impact and must be constituted such that, if it does fail, it does not break into knifelike, potentially life-threatening shards. Examples of *hazardous locations* subject to safety glazing requirements include glazing in and adjacent to doors, floor-to-ceiling glazing, shower and other wet area enclosures, glazing in guards and railings, glazing adjacent to stairs and ramps, and other large glass lites with their bottom edges close to the floor.

Most safety glazing must comply with the Consumer Product Safety Commission requirements identified as *CPSC 16 CFR Part 1201*. This standard establishes two categories of performance. *Category II glazing* has a higher impact resistance than *Category I glazing* and is required for larger pieces of glazing and glazing in the most hazardous locations.

In some applications, the building code also recognizes a separate but comparable standard, *ANSI Z97.1*, for compliance. Safety glazing must be permanently etched or marked in the factory with an indication of its testing compliance so that, once installed, it is possible to verify that appropriate products have been used where required. Tempered glass, heat-strengthened laminated glass, and some plastics can all be used in safety glazing applications.

Fire-Rated Glass

Fire-rated glass may be used in buildings in two ways: in its traditional role as glazing within fire door and fire window openings, or with higher-performing glass products, as a complete substitute for rated wall assemblies.

Fire-protection-rated glazing is used within fire-rated door and window openings. The glazing must pass one of several tests that demonstrate resistance to the passage of smoke and flame for the required duration, and if in a door or other location considered hazardous for human impact, also meet safety glazing criteria. Most such glazing is made from either specially tempered glass or transparent, optical quality ceramics.

Fire-resistance-rated glazing can substitute, in full, for opaque, fire-rated wall assemblies. To qualify for this application, the glazing must pass the same fire testing applied to walls and partitions, ASTM E119, a more stringent test than that applied to fire-rated doors and windows. (This test is explained further in Chapters 1 and 19.) In addition to preventing the passage of flame and smoke for the prescribed time period, the glazing must also protect combustible materials on the side of the glazing opposite the fire from ignition by preventing the transmission of radiant heat from the fire and limiting the rise in surface temperature of the glass itself on its non-fire side.

Fire-resistance-rated glazing consists of either a heat-absorbing polymer gel contained between two sheets of tempered glass, or thin layers of transparent intumescent material sandwiched between layers of annealed glass. When either type is exposed to the heat of fire, the gel or intumescent interlayers react to form opaque, insulating layers. As a result, these products not only resist the passage of flame and smoke, they also limit the rise in surface temperature of the glass on the side opposite the fire and prevent the transfer of radiant heat. Both of these types also meet safety glazing requirements. When used with a tested framing system, fire resistance ratings as great as 2 hours are possible.

Glass That Protects against Fading

Where protection from fading of interior finishes, fabrics, or artwork is important, glass products can be chosen that reduce the transmission of the most destructive components of the solar spectrum. These include ultraviolet light and some of the shorter-wavelength portions of the visible light spectrum. A glazing unit's ability to protect against fading is expressed as its *damage weighted transmittance* (*Tdw*). Tdw is a unitless measure that ranges from 0 to 1, with lower values indicating better protection. Ordinary clear glass has a Tdw of about 0.85, laminated glass, of 0.65, and common low-emissivity double-glazed units (discussed later in this section), of 0.50. Carefully designed glass units that combine tinting, low-emissivity coatings, and plastic interlayers can achieve Tdw values as low as 0.35 while remaining appreciably transparent. Tdw may also be indicated as *ISO-CIE Tdw* or *Tdw-ISO*, reflecting the standards-setting organizations from which the measure originated.

Fritted and Spandrel Glass

With *fritted glass*, paints consisting primarily of pigmented glass particles called *frit* are applied to the surface of the glass. The coating is dried and then fired in a tempering furnace, transforming it into a hard, permanent ceramic coating. Many colors are possible in both translucent and opaque finishes (Figure 18.10). By controlling the transparency and density of the fritted pattern, fritted glass can also be used to control the transmission of sunlight and heat into a space.

Frits are also used to create special opaque glass sheets for covering spandrel areas (the bands of wall around the edges of floors) in glass curtain wall construction (Figure 18.11). A uniform coating of frit is applied to what will be the interior surface of the glass. Some *spandrel glasses* are made as similar as possible in exterior appearance to the window glass that will be used above and below the spandrels. But it is difficult to make the spandrels indistinguishable from the windows under all lighting conditions, so most spandrel glasses are made to contrast with the adjacent window areas. Spandrel glass is usually tempered or heat strengthened to resist the thermal stresses caused by solar heating behind the spandrel.

Tinted and Reflective Coated Glass

Tinted and reflective glass products are used to reduce unwanted sunlight from entering a building in order to reduce visual glare and unwanted solar heating within the building.

Tinted Glass

The transparency of glass to visible light is called its *visible light transmittance* (*VT*). It is measured as the ratio of visible light that passes through the glass relative to the amount of light striking the glass. Clear glass has a visible light transmittance in the range of 0.80 to 0.90, meaning that 80 to 90 percent of the visible light striking the glass passes through. The remaining 10 to 20 percent is either reflected or absorbed by the glass and converted to heat.

FIGURE 18.10
Fritted patterns modulate the sunlight that enters a theater lobby. *(Photo of Pilkington Planar system by W&W Glass Systems, Inc.)*

Tinting glass reduces its visible light transmittance. *Tinted glass* is made by adding small amounts of selected chemical elements to the molten glass mixture to produce the desired hue and intensity of grays, bronzes, blues, greens, and golds. The visible light transmittance of tinted glasses ranges from about 0.75 in the lightest tints to 0.10 for dark gray. The overall reduction in solar heat gain is often significantly less, however, because the solar radiation absorbed by the glass and converted to heat must go somewhere, and a substantial portion of it is conducted or reradiated to the interior of the building.

The effectiveness of glass in reducing heat gain from solar radiation is described as its *solar heat gain coefficient* (*SHGC*); this is the ratio of solar heat admitted through a particular glass to the total heat energy striking the glass. Solar heat gain coefficient accounts for the solar radiation that passes through glass, as well as for heat that is conducted or radiated into the space due to heating of the glass itself. Clear glass has a solar heat gain coefficient ranging from about 0.90 to 0.70, depending on its clarity and thickness. Solar heat gain coefficients for tinted glasses range from about 0.70 to 0.35, meaning that these glasses allow 70 to 35 percent of the solar energy striking the glass to pass through. In buildings dominated by cooling, glass with a low solar heat gain coefficient is used to minimize unwanted solar heating.

Visible transmittance and solar heat gain coefficient can be combined to determine the *light to solar gain (LSG) ratio*, a useful measure of the overall energy-conserving potential of glass. The light to solar gain ratio ratio is defined

FIGURE 18.11
An urban office tower combines a slightly darker-hued spandrel glass with lighter-hued insulated glass units for the windows. *(Photo by Joseph Iano.)*

as the visible light transmittance divided by the solar heat gain coefficient. A glass with a high light to solar gain ratio ratio admits a relatively large portion of visible light in comparison to the amount of solar heat admitted, combining the greatest daylighting potential with the least solar heating. Green- and blue-tinted glasses tend to have high light to solar gain ratio ratios, whereas those of bronze, gold, and gray tints tend to be lower.

Reflective Coated Glass

Thin, durable films of metal or metal oxide can be deposited on the surface of either clear or tinted glass sheets to make *reflective coated glass*, also called *solar control glass*. Depending on its composition, the film may be applied to either the inside of the glass or the outside. While remaining thin enough to see through, the film reflects a substantial portion of the incident visible light. Visible light transmittance and solar heat gain coefficients for reflective coated glasses vary significantly, depending on the density of the metallic coating and the tinting of the glass to which it is applied. Reflective coated glasses appear as mirrors from the outside on a bright day. At night, with lights on inside the building, they appear as dark but transparent glass.

Who when he first saw the sand and ashes. . . would have imagined that in this shapeless lump lay concealed so many conveniences in life. . . . [B]y some such fortuitous liquefaction was mankind taught to procure a body at once in a high degree solid and transparent; which might admit the light of the sun, and exclude the violence of the wind; which might extend the sight of the philosopher to new ranges of existence. . . .

—Dr. Samuel Johnson, writer and lexicographer, *The Rambler*, April 17, 1750

Insulating Glass

Glass, on its own, is a poor thermal insulator. A single sheet of glass (*single glazing*) conducts heat about 5 times as fast as 1 inch (25 mm) of polystyrene foam insulation and 20 times as fast as a well-insulated wall. A second sheet of glass applied to a window with an airspace between the two sheets (*double glazing*) cuts this rate of heat loss in half, and a third sheet with its additional airspace (*triple glazing*) reduces the rate of heat loss to about a third of the rate through a single sheet. A triple-glazed window, however, still loses heat many times faster than the wall in which it is placed.

To prevent moisture condensation within such *insulating glass units*, or *IGUs*, the units are hermetically sealed around the edges at the time of manufacture with dry air pumped into the space between the lites. A hollow metal *edge spacer*, or *spline*, is inserted between the edges of the sheets of glass, and the edges are closed with a sealant compound. A small amount of a chemical drying agent, or *desiccant*, inside the spacer remains in the finished unit to remove residual moisture from the trapped air or from air that seeps into the unit after manufacture. When an insulating glass unit does exhibit internal condensation, it is usually a sign of failure of the edge seal, at which point the unit must be replaced. To increase the longevity of the insulating glass unit, a *dual seal spacer*, combining a primary butyl seal with a secondary seal of silicone, urethane, or other organic sealant, may be used (Figure 18.12).

Because the edge seals are more conductive of heat than the glass-only portions of an insulating glass unit, they tend to lower the thermal efficiency of the unit as a whole. Making the spacer from a less conductive metal, such as stainless steel instead of aluminum, is one way to improve thermal performance. To achieve more significant efficiency gains, *warm edge spacers*, made of thermally broken aluminum and plastic or of extruded rubber or dense foam, are used. Warm edge spacers also result in a more uniform surface temperature across the entire inner surface of the glazing, increasing occupant comfort and reducing the chance of condensation around the inner edges of the unit. Very high-efficiency warm edge spacers may have thermal conductivities as little as one-tenth that of traditional aluminum edge seals (Figure 18.12).

The thickness of the airspace in insulating glass units is less critical to the units' insulating value than the mere presence of the airspace: From ⅜ inch (9 mm) up to about 1 inch (25 mm) of thickness, the insulating value of the airspace increases somewhat, but above that thickness little additional benefit is gained. The most common overall thickness for large, double-glazed lites is 1 inch (25 mm), which results in an airspace ½ inch (13 mm) thick if ¼-inch (6-mm) glass is used.

The thermal performance of insulated glazing units can also be improved by introducing gasses with greater density and lower thermal conductivity than that of ordinary air into the space between the sheets of glass. Depending on the gas used and the thickness of the space, improvements in thermal performance of 12 to 18 percent are possible. Argon and krypton are the gasses most commonly used.

The performance of glazing as a thermal insulator is quantified as its *U-Factor*. U-Factor is expressed as BTUs per square foot-hour-degree Fahrenheit (BTU/ft²-hr-°F) or, in metric units, as watts per square meter-degree Kelvin (W/m²-°K). U-Factor is the mathematical reciprocal of R-value, and as such, lower values represent improved thermal performance. Some examples of glazing configurations and their U-Factors and R-values are listed in Figure 18.13.

The performance of insulated glazing units can also be improved by evacuating most of the air from the space between the glass sheets. In such *vacuum-insulated glazing*, glass sheets are spaced relatively close together, separated by a barely perceptible array of small-diameter spacers that prevent the sheets from bowing inward due to the difference in air pressure on their two sides. Units as little as ¼ inch (6 mm) in thickness can replace single glass in existing windows, with minimal visual impact but providing thermal performance comparable to conventional double glazing. They can also be used as one lite in an otherwise conventionally

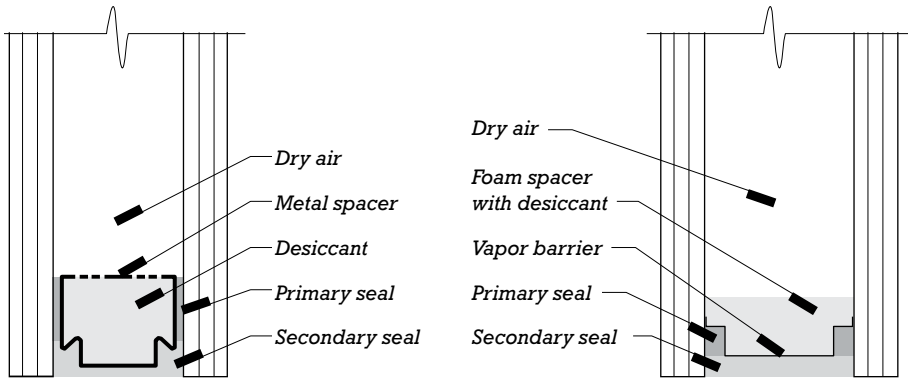


Figure 18.12

***Left*, a dual-sealed metal spacer for a double-glazed unit. The spacer is filled with desiccant. Small holes in the inward-facing side of the spacer allow the desiccant to absorb moisture from the airspace. *Right*, one type of warm edge spacer, also dual-sealed. The thin foil vapor barrier between the foam spacer and seals prevents moisture diffusion into the dry air space. Desiccant is embedded within the foam.**

constructed double- or triple-glazed insulating unit. Higher-performing units that incorporate low-emissivity coatings (see the next section) may have U-Factors as low as 0.08 BTU/ft²-hr-°F (0.5 W/m²-°K), in units only roughly ½ inch (12 mm) thick.

Low-Emissivity Coated Glass

The thermal performance of glazing can be improved substantially by the use of glass with a *low-emissivity* (*low-e*) *coating*. Low-e coatings are ultrathin, virtually transparent, and almost colorless metallic coatings that selectively reflect solar radiation at different wavelengths. They have a high visible light transmittance and, depending on the particular coating, a low transmittance for some or all types of infrared radiation (heat).

Low-e coated glass is most commonly used as one of the two lites in a double-glazed unit. By reducing the radiant transfer of heat between the lites, the overall thermal transmittance of the glazing unit is reduced. This allows low-e double glazing to meet or exceed the thermal performance of ordinary triple glazing. Low-e coatings that reflect the majority of the infrared component of solar radiation can also provide high visible light transmittance with low solar heat gain, allowing such units to achieve high light to solar gain ratios (Figures 18.13 and 18.14).

	VT	SHGC	LSG	U[a]	R[b]
Single glazing, clear	0.90	0.85	1.3	1.1 *6.3*	0.91 *0.16*
Double glazing, clear	0.79	0.70	1.1	0.47 *2.7*	2.1 *0.37*
Double glazing, medium gray tinted	0.40	0.45	0.9	0.47 *2.7*	2.1 *0.37*
Triple glazing, clear	0.53	0.52	1.0	0.34 *1.9*	2.9 *0.52*
Double glazing, clear, low-e, low SHGC	0.64	0.27	2.4	0.28 *1.6*	3.6 *0.63*
Double glazing, low-e, high SHGC, argon filled	0.78	0.63	1.2	0.27 *1.5*	3.7 *0.65*
Triple glazing, clear, low-e, medium SHGC, krypton filled	0.65	0.50	1.3	0.15 *0.85*	6.7 *1.2*

[a]U-Factor: BTU/ft²-hr-°F followed by *W/m²-°K*.

[b]R-Value: ft²-hr-°F/BTU followed by *m²-°K/W*.

FIGURE 18.13

Comparative properties of sample glass units. Note the high light-to-solar-gain ratio possible with low-e double glazing. Higher LSG values indicate better energy efficiency of the glazing unit in buildings where cooling loads dominate. U-Factors and R-values are center-of-glass values and, for the insulating glass units listed, do not account for reduced thermal performance around the edges due to the greater conductivity of the spacers. The lower the U-Factor or higher the R-value, the better the thermal insulating performance of the unit.

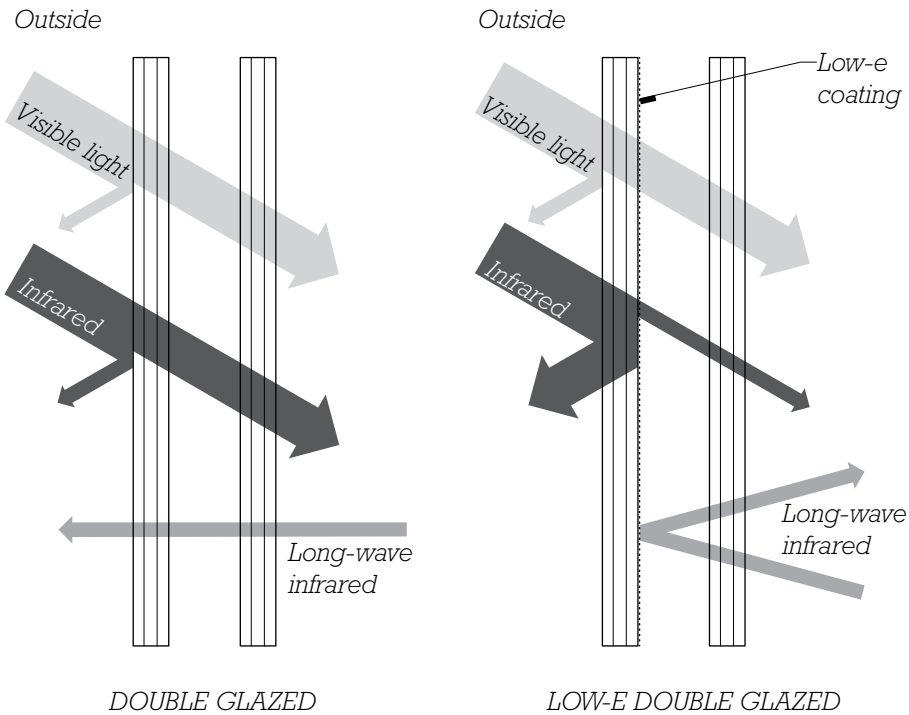


FIGURE 18.14

Diagrams illustrating the responses of ordinary and low-e double glazing to visible light and radiated heat. Without a low-e coating the unit transmits roughly 80 percent of visible light and 70 percent of the sun's infrared radiation. It also does little to limit radiative heat losses (long-wave infrared) from the interior. The low-e coated unit transmits roughly 65 percent of visible light, but only 25 percent of the sun's infrared radiation. The coating also reflects heat radiating from the interior. In this example, the coating is shown on the number 2 surface of the unit.

By varying the properties of the low-e coating and by combining it with different types of tinted glass, the performance characteristics of the glazing unit can be tailored to meet different needs. For buildings dominated by wintertime heating loads, low-e units with high U-Factors (to minimize heat loss) and high solar heat gain coefficients (to promote wintertime solar heat gains) may be selected. For buildings dominated by cooling loads, units with low solar heat gain coefficients (to minimize solar heating) are used (Figures 18.13 and 18.15).

The performance of a low-e coating is also affected by its position within the insulated glass unit. By convention, the glass surfaces in a glazing unit are identified by *glass surface number*, starting from the exterior side of the unit and working inward. For example, in a double-glazed unit, the outward face of the outer glass lite is surface number 1 and the inward face of this lite is surface number 2. The outward and inward faces of the inner lite are surfaces number 3 and 4, respectively. In a double-glazed unit, the low-e coating is most commonly located on the number 2 surface. However, where greater solar heat gain is desired, the coating may be located on the number 3 surface. Or, an additional low-e coating may be applied to the number 4 surface to reduce radiant exchange between room occupants and the glass, thereby improving thermal comfort.

Low-e coatings can also be applied to very thin membranes of transparent plastic. One or two of these plastic films can be installed within the airspace or gas space of a double-glazed unit, stretched tight, parallel to the sheets of glass, where they act as virtually weightless additional glazing elements (see Figure 19.9).

Glass for Structural Use

Even in traditional applications, glass must sometimes reliably resist structural loads. Glass in any exterior window, storefront, or curtain wall must withstand the pressures of the wind without deflecting too much or breaking. Overhead glass must resist the weight of snow, and

Figure 18.15
Low-e, low-SHGC glazing on the southwest façade of a university lab sciences building. *(Architect: ZGF. Photo by Joseph Iano.)*

Figure 18.16
A detail of the glass staircase shown in the chapter opening image. A typical configuration for laminated glass used as flooring might range from 1 to 2 inches (25 to 50 mm) thick, with individual laminations ⅜ to ½ inch (10 to 12 mm) thick. *(Photo by Joseph Iano.)*

Interactive Exercise

glass guardrails, the force of human impact. In other cases, glass is used where, in the past, only conventional structural materials were feasible. For example, vertical glass fins acting as structural beams can stiffen tall glass walls (Figure 18.25). And, glass can be used to support the weight of people and even vehicles in stair treads, walkways, and floors (Figure 18.16).

Glass itself is a brittle material (when overstressed, it breaks suddenly, without warning) and by the nature of its manufacturing process includes unavoidable defects that make its strength unpredictable. For these reasons, the structural design of glass assumes that for any given parameters, a certain number of units will fail. For example, according to the ASTM E1300 standard, design of window glass subjected to wind loads incorporates an expected failure rate of 8 lites out of each 1000. Or, when designing a more critical application, such as glass flooring, a lower expected failure rate may be used, such as no more than 1 in 1000 units, resulting in more conservative stress limits in the glass.

To overcome the brittle nature of glass in critical structural applications, it is laminated. In this way, failure of any one lite does not mean failure of the entire laminated unit. In glass flooring applications, three or more layers of glass may be used and the assembly designed such that the failure of any one layer will leave enough structural capacity in the remaining intact layers to continue to support design loads, at least for a limited period of time. Stronger interlayer materials may also be used. For example, ionoplast is more than 100 times stiffer and 5 times stronger than PVB, and when used as the interlayer material, results in stronger, tougher, and more durable assemblies. Heat-strengthened or tempered glass lites can be used, reducing the thickness and weight of the laminated assembly (though trade-offs in the optical clarity and failure behavior of these different glass types must also be considered). And laboratory testing and sophisticated computational techniques are used to validate designs and assure a full understanding of the stresses within the glass and the glass behavior.

Other Types of Glass

Glass can be produced with an amazing range of physical properties and appearance. *Low-iron glass* has greater optical clarity than ordinary annealed glass. *Antireflective glass* minimizes reflections that occur when light levels differ significantly on opposite sides of the glass. It is used, for example, for glazing in showrooms, display areas, and sports stadiums. *Silk-screened* or *digitally printed glass* allows for the addition of complex graphics to both interior and exterior applications.

Self-cleaning glass is coated with titanium oxide on its exterior surface, enabling sunlight to convert dirt, dust, and other organic particles on the glass to carbon dioxide and water.

Glass that can change its optical properties is called *chromogenic glass*. *Thermochromic glass* becomes darker when it is warmed by the sun. *Photochromic glass* becomes darker when exposed to bright light. Both types are potentially useful as passive devices to reduce cooling loads in buildings. *Electrochromic glass* changes its transparency in response to the passage of electric current. Also called *switchable glass*, it can be actively controlled by building occupants or automated systems in response to changing requirements for control of solar heat gain, daylighting, or occupant privacy.

Chemically strengthened glass is produced by an ion exchange that takes place when annealed glass is immersed in a molten salt bath. This process results in a prestress in the glass similar to that which occurs with heat-treating. However, because the temperatures involved are lower, the chemical strengthening occurs without causing optical distortions.

Mirror glass has a thin, reflective, silver-based coating on its back side. To prevent corrosion of the silver and provide additional protection, a thin layer of copper is applied over the silver and a backing paint is applied over the copper. *Patterned glass*, which is hot glass rolled into sheets with different surface patterns and textures, is used where light transmission is desired but vision must be obscured for privacy. Glass manufactured with a high percentage of lead oxide can be used as *radiation-shielding glass*. *Photovoltaic glass* is coated with a thin film of amorphous silicon that generates electricity from sunlight, and can thus help reduce a building's electricity consumption. Traditional *stained glass* and contemporary *colored glass*, formulated with ingredients that alter the color of the glass, can be used in a wide range of artistic and architectural applications. Glass may be blown, cast, fused, and colored to produce an infinite variety of types of *art glass* used for decorative and sculptural purposes.

Plastic Glazing

The two most common plastic glazing materials are *acrylic* and *polycarbonate*. Both offer good clarity and weather-resistance. Both are softer, more easily scratched, and more expensive than ordinary float glass. And both have high coefficients of thermal expansion, which cause them to expand and contract with temperature changes more than glass. Acrylic glazing is two to three times more impact-resistant than annealed glass of the same thickness. Polycarbonate sheets have even greater impact resistance and can also be formulated for resistance to fire.

Acrylic and polycarbonate sheets can be manufactured in a variety of colors and with varying degrees of transparency. They are easily machined, and as thermoplastics, can be heat-formed, such as for domed skylights. Low-e coatings can be applied to acrylic sheets to improve the thermal properties of the glazing. Polycarbonate sheets can be manufactured in a double-walled configuration, called *cellular polycarbonate glazing*, creating hollow panels, roughly ¼ inch to 1½ inch (6 to 40 mm) thick, with enhanced stiffness and thermal performance. These materials can also meet safety requirements for glazing used in areas subject to human impact.

Glass-fiber-reinforced polyester (*fiberglass*) glazing is durable and long-lasting, and can be formulated with varying degrees of translucency (though never full transparency) and resistance to fire. Fiberglass sheets are frequently applied as a facing material over lightweight aluminum frames to make translucent composite panels with higher thermal efficiencies. In corrugated form, fiberglass sheets are used as a utilitarian, translucent roofing material.

Ethylene tetrafluoroethylene (*ETFE*) is a translucent, thin, extruded plastic sheet material (also referred to as a foil) chemically similar to Teflon. It transmits 85 to 95 percent of visible light and is lightweight, strong, long-lasting, and recyclable. Its light weight—approximately 1 percent that of glass—results in lighter and less costly supporting structures than required with glass. The material can be stretched between a surrounding frame or supported with a cable network. Single-ply membranes have roughly the same insulating value as a single sheet of glass. Air-inflated pillows, made of two or more plies, achieve higher thermal efficiencies. Such multi-ply systems also require a network of inflation tubes connected to pumps to maintain pressure within the pillows. The material itself can be printed, tinted, or manipulated in other ways to adjust its light transmission and solar heat gain properties.

Glazing

Glazing Small Lites

Figure 18.17 illustrates common glazing techniques suitable for various frame materials and a range of glass unit sizes. In (*A*), a simple wood sash is site-glazed with a single glass lite. The glass is set in glazing compound or caulk and secured in place with a wood *stop*. The stop is fastened to the window sash with fine finish nails or screws (not shown in the figure). Traditional *glazing compounds* are made from mineral oils and organic filler. They adhere well to glass, remain sufficiently elastic to accommodate small movements in the glass, and when painted, provide good weather resistance. Alternatively, low- or medium-range gunnable sealants can be used. In (*B*), a double-insulated glass unit is factory-glazed into a wood sash. Resilient setting pads provide support and cushion the glass edges. On the exterior side, silicone sealant acts as the primary weather seal and as adhesive to hold the glass in place. A thinner bed of sealant cushions the glass on the interior side, and a wood stop, mechanically attached or glued in place, secures the glass within the frame. Other frame materials may also be used, such as vinyl, aluminum, or fiberglass. Glazing systems such as these are suitable for door and window systems not subject to large wind forces or large movements due to thermal expansion and contraction within the glass or frame.

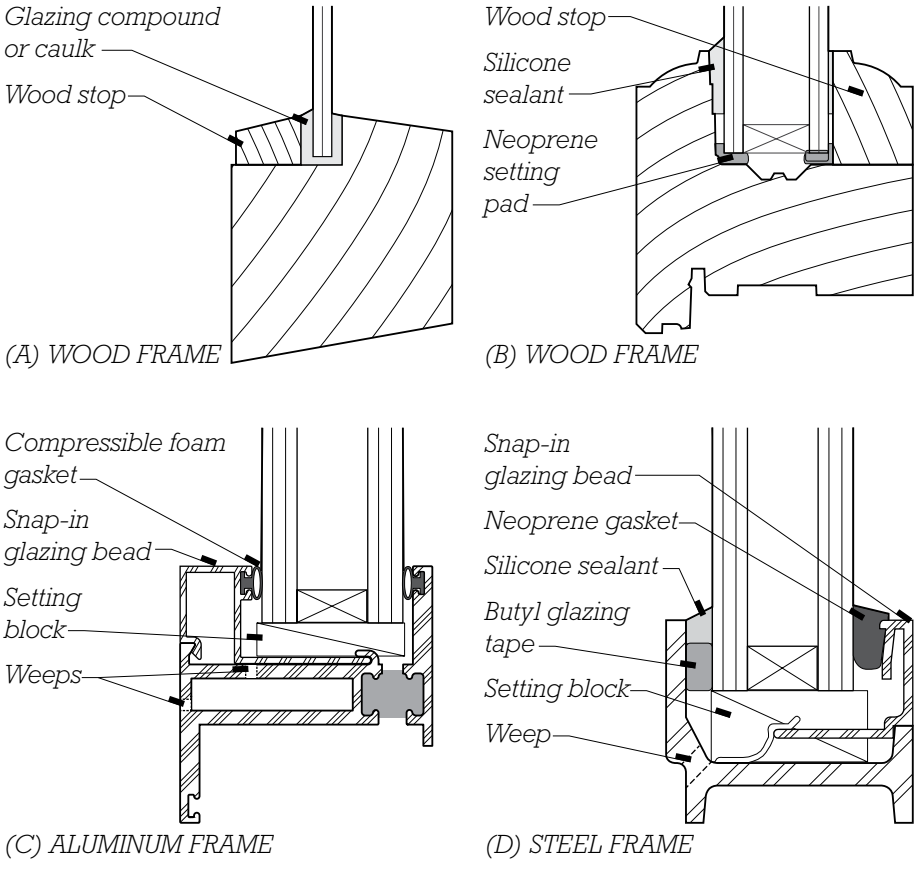


Figure 18.17
Examples of glazing techniques. The exterior is always to the left. All have removable stops or glazing beads, to allow for glass replacement. Examples (*A*) and (*C*) are *exterior glazed*, requiring access from the outside of the unit for replacement. Examples (*B*) and (*D*) are *interior glazed*.

Glazing Large Lites

Glazing for larger glass units must secure the glass against larger wind forces, resist the passage of water and air under more severe exposures, and accommodate larger differential movements between the glass and frame. This last point means that:

- The glass must be securely supported yet gently cushioned where it is held by the frame.
- The glass and frame must be able to expand and contract independently with changes in temperature.
- The edges of the glass must be free to rotate slightly as the glass deflects under wind loads.
- Contact between glass edges and the frame must be avoided to prevent damage to the glass.

Figure 18.17*C* and *D* illustrate two such approaches. In both, the glass is lifted off of the frame and its weight supported on synthetic rubber or silicone *setting blocks*, normally two

Figure 18.18
A single-glazed steel sash system creates a thin, delicate pattern of glass and steel. However, single glass and solid steel mullion window systems cannot meet contemporary energy code requirements for thermal efficiency. *(Photo by Joseph Iano.)*

per lite, located at the quarter points of the bottom edge of the lite. For support against wind loads, a specified amount of *bite* (depth of grip on the edges of the glass) is provided. If the bite is too small, the glass may pop out of the frame under strong wind pressures; if too large, the glass edges may not be able to rotate freely when the glass deflects.

In (*C*), compressible foam gaskets cushion the sides of the glass within the glazing pocket and provide sealing against water and air leakage. An extruded aluminum *glazing bead*, which can be snapped into and out of the frame, secures the glass in place. In (*D*), the exterior-side seal is a combination of solid butyl tape and silicone sealant. Together, these materials maintain a controlled joint width between the glass and frame, hold the glass firmly, and provide a high degree of resistance to the leakage of air and water. On the interior side, a preformed rubber gasket and extruded aluminum snap-in glazing bead clamp the glass unit within the frame. Both of these examples illustrate how glass can be secured against large wind loads while also allowing for movement between the glass and frame.

These two examples also illustrate the application of pressure-equalized design to control the passage of water through the glazing system. (For an explanation of pressure-equalized design, see Figure 16.8 and the accompanying text.) Water that finds its way past the exterior glazing seals collects in the hollow space within the frames. The gaskets on the interior side of the frame act as air barriers that neutralize wind pressures and prevent the water from being driven further inward. Small ports, or *weeps*, in the bottoms of the frames allow the water to drain back to the exterior. The setting blocks that support the glass units also elevate the bottom edges of the units above any water in the frame.

Most glazing systems are assembled with glazing materials in configurations similar to those illustrated in Figure 18.17. In general, *dry glazing* components, such as synthetic rubber gaskets, are quick and easy to install, consistent in profile, and relatively free from variations in workmanship during installation. However, the lack of adhesion between glass and frame may permit the glass to shift position within the glazing pocket. *Wet glazing* components, such as silicone sealants, adhere glass to frame and form more complete air- and watertight seals—when installed with adequate care. *Solid glazing tapes*, such as butyl or polyisobutylene, also adhere glass to frame and can maintain consistent, controlled joint depths.

Advanced Glazing Systems

In *butt-joint glazing*, the head and sill of the glass sheets are captured conventionally in metal frames. But vertical mullions are eliminated entirely, with only silicone seals between glass joints. Butt-joint glazing produces windows with strong, unbroken horizontal bands of glass (Figure 18.20).

Where the appearance of *flush glazing* is important from the exterior, but vertical glass edges require support, these edges can be adhered to an interior mullion with structural silicone sealant (structural adhesives are described in more detail later in

Figure 18.19
Insulated glass units weighing close to 200 pounds (90 kg) each are stacked on a wheeled dolly. Vacuum suction cups with handles are used to grasp the units. *(Photo by Joseph Iano.)*

Figure 18.20
A floor-to-ceiling mullionless butt-joint glazing system uses only a silicone sealant joint at the vertical joints in the glass.
(Photo by Joseph Iano.)

this section). The top and bottom edges of the glass units are captured conventionally (Figure 18.21).

Figure 18.22 illustrates a flush glazing system, in which glass edges are captured with a *pressure bar* (or *pressure plate*) concealed within the depth of the double-glazed unit. Both the horizontal and vertical joints can be flush-glazed.

In *structural glazing*, glass units are not mechanically captured at all, but rather held in place solely with *structural glazing adhesive* (Figures 18.23 and 18.24). Both *structural silicone sealant* and *acrylic foam structural glazing tape* are used for this purpose. These adhesives are strong and permanent enough to reliably hold the glass while resisting wind pressures, thermal stresses, and other forces that act on the glass over the life of the window system. Usually the application of the adhesive occurs in the factory under controlled conditions where the quality of the bond can be assured. The glass units are adhered to fittings, such as the aluminum channels shown in Figure 18.23. In the field, the glazed assemblies are then attached to the framing.

In *point-supported glazing*, glass units are held only at their corners, and both horizontal and vertical joints are flush-glazed with silicone seals. The hardware used in this system provides support against gravity and lateral forces while not imparting unwanted bending or torsional stresses into the glass. A *glass mullion system* relying on point-supported glazing is shown in Figure 18.25, a cable *suspended glazing* system is shown in Figures 18.26 and 18.27, and a point-supported overhead glazing system is shown in Figures 18.28 and 18.29.

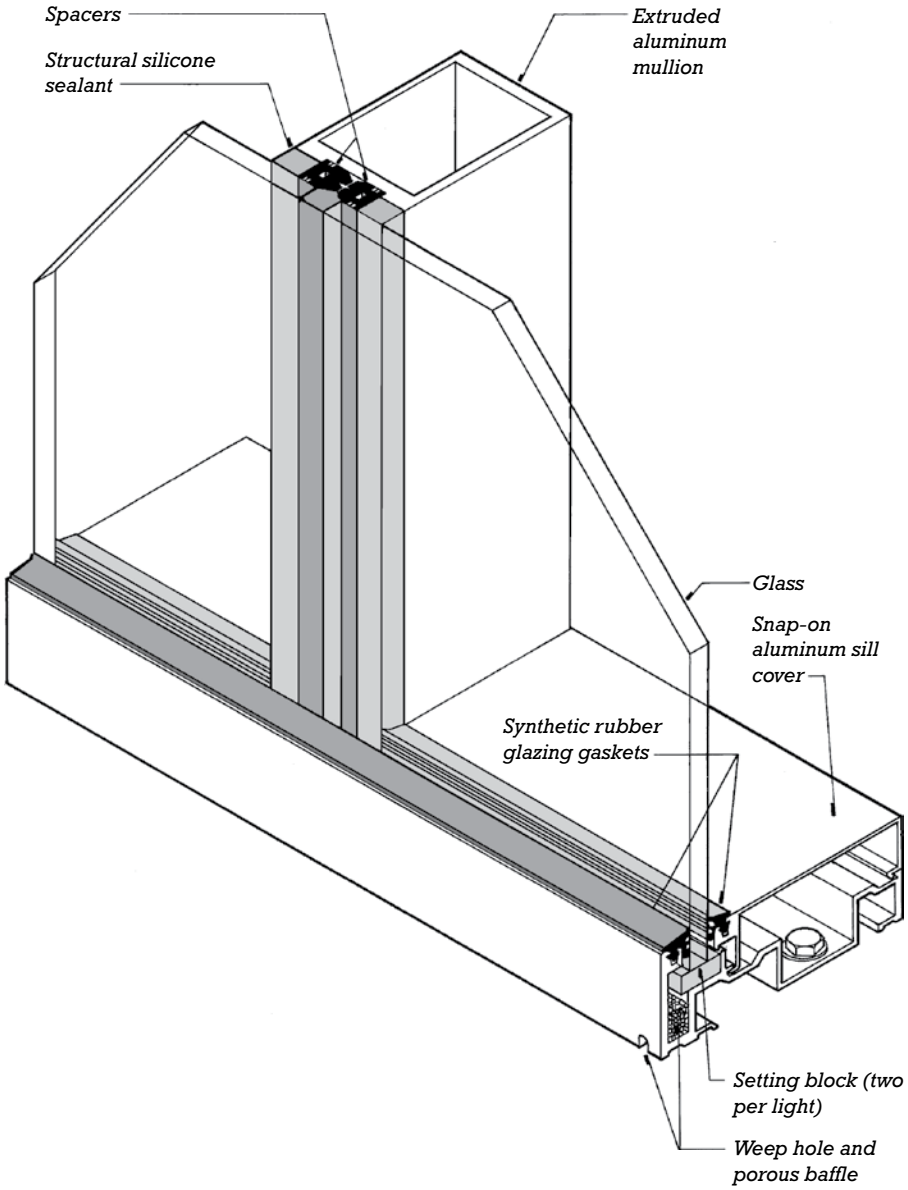


FIGURE 18.21

In this flush glazed window system, vertical glass edges are adhered to interior mullions with structural silicone sealant. The sill and head are conventionally glazed, using snap-on aluminum covers. *(Courtesy of PPG Industries.)*

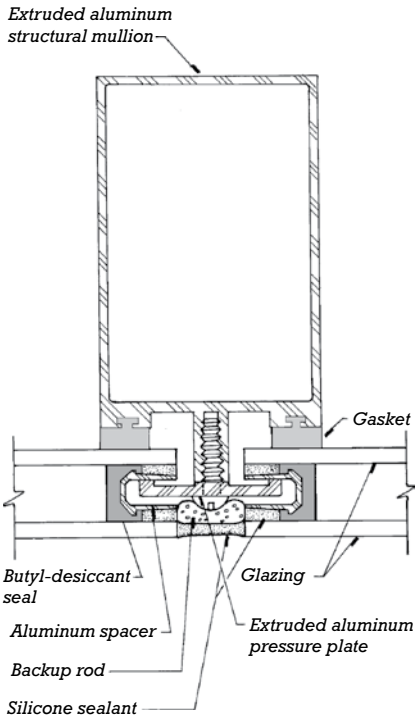
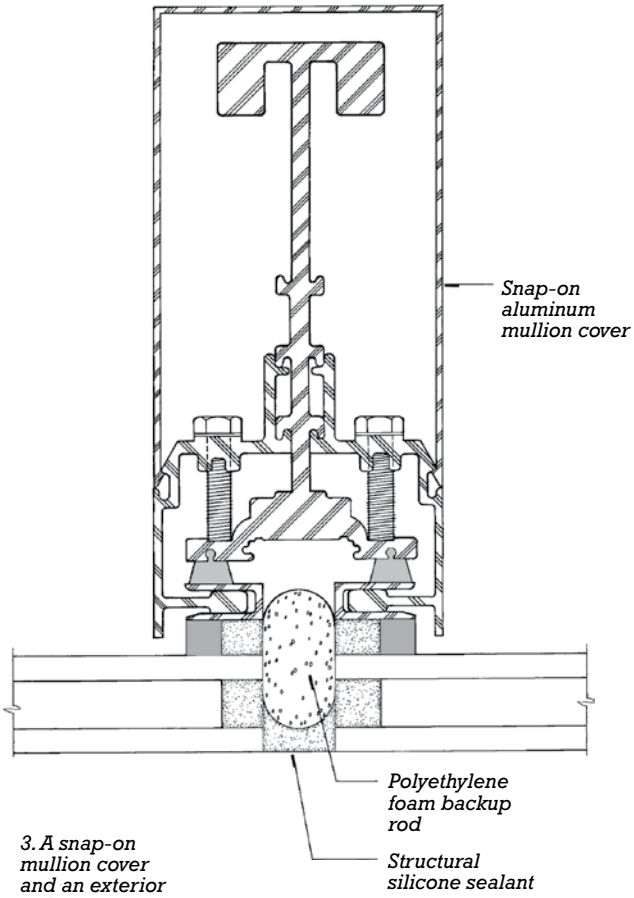
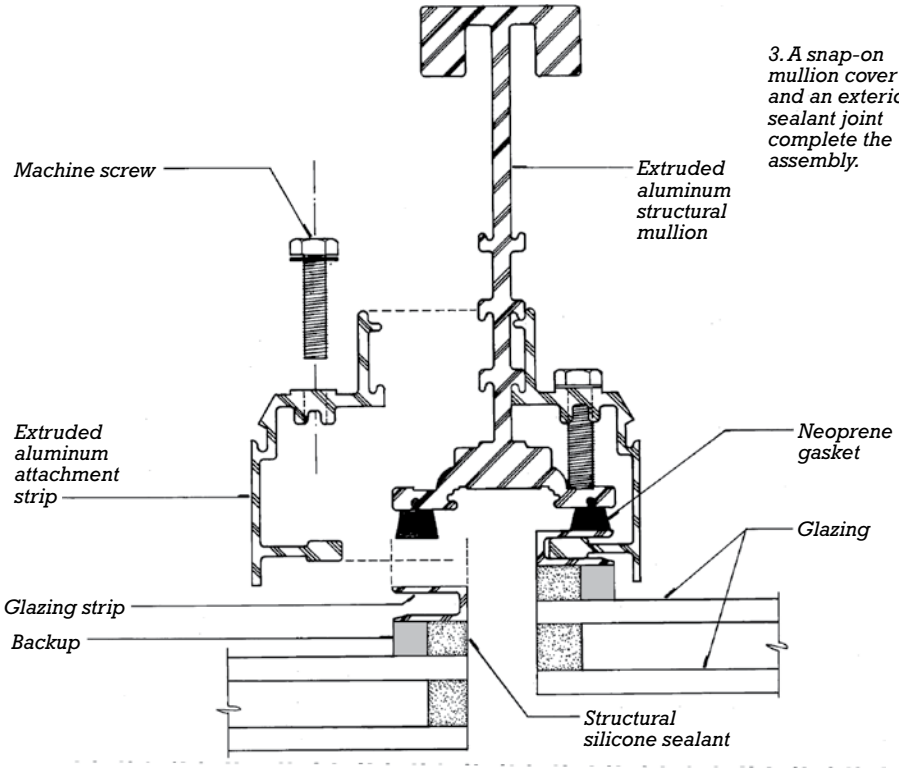


FIGURE 18.22
A flush glazing system with the pressure bar concealed within the glazing. A glass unit slightly wider than normal may be required. Desiccant required to remove residual moisture from the airspace is mixed with the butyl spacer material. Regularly spaced, discrete clamping hardware called "toggles" may also be used instead of the continuous bar.



3. A snap-on mullion cover and an exterior sealant joint complete the assembly.



1. Glazing is factory fabricated with metal glazing strips adhered to the glass using structural silicone sealant.

2. The machine screw and attachment strip clamp the glazing unit into place.

FIGURE 18.23
Steps in the assembly of a mullion for a four-sided structural silicone exterior flush glazing system. The internal complexities of the aluminum components and sealant are completely concealed when the installation is finished. From the inside, one sees only a simple rectangular aluminum mullion, and from the outside, only glass and a thin bead of silicone sealant. *(Copied by permission from PPG EFG System 712 details, courtesy of PPG Industries.)*

Figure 18.24
Structural silicone glazing on the exterior of this port public arrival building. Solid wall areas are clad with vertical Douglas fir 4 × 4 (89 × 89 mm) screening, prefinished wood veneer panels, and composite aluminum panels. The structure is framed with glue-laminated wood and structural steel. *(Courtesy of Checkwitch Poiron Architects,* **www.checkwitchpoiron.com**.*)*

Figure 18.25
The glass mullion system in the Magic Johnson Theater in New York City uses low-iron glass to maximize transparency, an effect that is accentuated by suspending the glass from above, using only vertical glass stiffeners (fins) to resist wind loads. *(Photo of Pilkington Planar system by W&W Glass Systems, Inc.)*

Figure 18.26
This suspended, point-supported glazing system relies on anticlastic curvature (compound concave and convex curvature) and a system of tension cables to give the glass wall resistance to both positive and negative wind forces. The surrounding structure must be strong enough to resist the tensile forces in the cables. *(Photo by Joseph Iano.)*

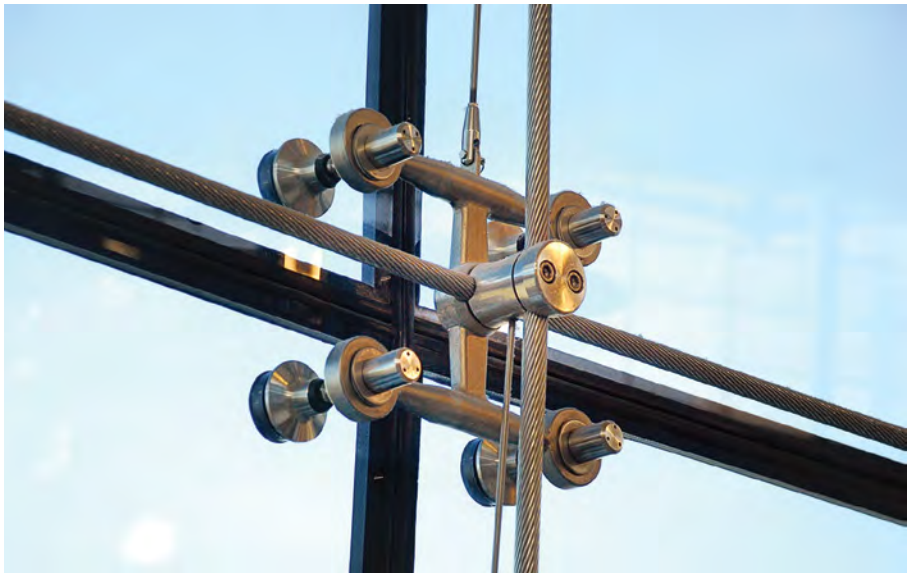


Figure 18.27
A point-supported "spider fitting" used in the glazing system shown in Figure 18.26. The combination of parts allows rotation in any plane and also prevents the fitting from introducing unwanted stresses into the glass when the wall deflects under varying loads. *(Photo by Joseph Iano.)*

Figure 18.28
Airside 2 Terminal at Orlando International Airport, designed by HOK Architects, features large areas of insulating laminated glass units. Laminated glass fins serve as beams to conduct the weight of the roof to vertical stainless steel rods that are supported by a stainless steel cable tensile structure. The downward-hanging cables transmit the weight to the stiff steel pipe trusses around the perimeter, which also resist the inward pull of the cables. The upward-arching cables hold the glass surface down against possible suction forces exerted by wind. Frit was used to diminish reflected glare on glass facing the control tower, and low-e coatings were applied to the insulating glass. *(Photo of Pilkington Planar system by W&W Glass Systems, Inc.)*

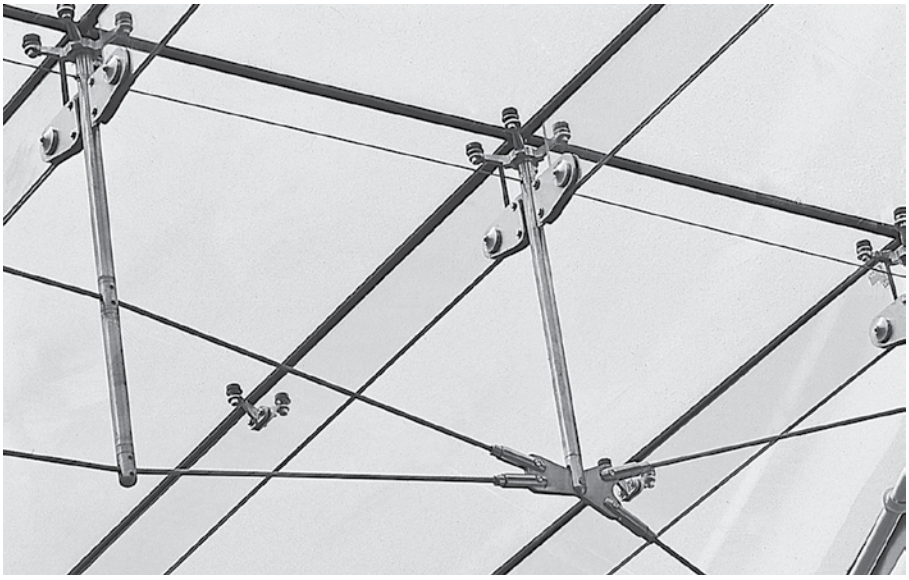


Figure 18.29
A detail of the glass roof supports in Figure 18.28.The four-point and two-point stainless steel spider fittings attach the glass components to each other and to the metal supporting structure. *(Photo of Pilkington Planar system by W&W Glass Systems, Inc.)*

Glass and Energy

Glass is a two-way pipeline for the flow of both conducted and radiated heat. Even when doubled or tripled, glass conducts heat rapidly into or out of a building. It can also admit large amounts of solar heat into a building.

Imagine a city iridescent by day, luminous by night, imperishable! Buildings, shimmering fabrics, woven of rich glass; glass all clear or part opaque and part clear, patterned in color or stamped to harmonize with the metal tracery that is to hold it all together, the metal tracery to be, in itself, a thing of delicate beauty consistent with slender steel construction.. . .

—Frank Lloyd Wright, *Architectural Record*, April 1928

In residential buildings, the conduction of heat through glass should be minimized in the extremely hot or cold seasons of the year. Double glazing, low-e coatings, low-conductivity gas fills, and snug curtains or shutters are desirable features for residential windows. Warming sunlight is welcome in winter but undesirable in summer, which leads the conscientious designer to orient major windows toward the south, with overhangs or sunshades above to protect them against the high summer sun. Large east or west windows can cause overheating in summer and should be avoided unless they are shaded by nearby trees or other features.

In larger nonresidential buildings, heat generated within the building by lights, people, and equipment is often sufficient, or more than enough, to maintain comfort throughout much of the year. For this reason, controlling unwanted heat gain is often an important consideration for window systems in larger buildings. Tinted, mirrored, and low-e coated glass units with low solar heat gain coefficients are common choices. East and west windows can be especially problematic, as they contribute strongly to summertime overheating and are difficult to shade. Shades or blinds inside the glass are helpful in eliminating the glare, but they do less to keep out the heat, because once sunlight strikes them its heat is already inside the building and little of it will escape.

Glass in buildings also plays an essential role in daylighting strategies. Natural daylight improves occupant well-being and efficiency. It also saves energy by reducing the consumption of electricity for artificial lighting and reducing cooling loads on the building air conditioning system.

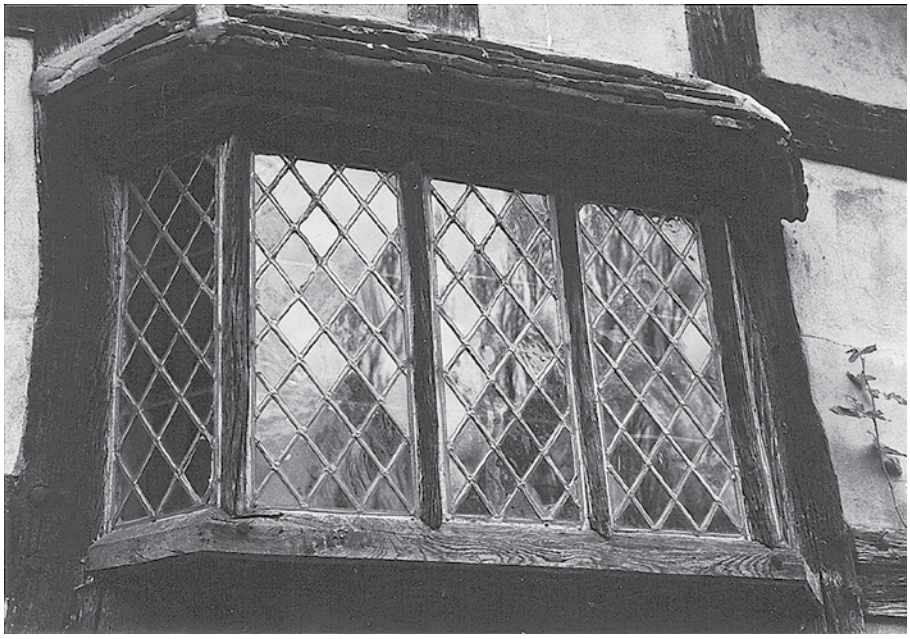


Figure 18.30
Leaded diamond-pane windows of handmade rolled glass in an Elizabethan English bay window. *(Photo by Edward Allen.)*

Glass and the Building Codes

Building codes are concerned with the structural adequacy of glass against wind and impact loads, its role in providing natural light in habitable rooms, its breakage safety, its ability to prevent the spread of fire through a building, and its contribution to the energy consumption of a building.

The International Building Code provides structural criteria for determining the necessary thicknesses of glass to resist wind and other structural loads. In coastal regions where hurricanes are common, the code also requires windows or window coverings to meet requirements for resistance to the impact of objects blown against glazed areas by high winds.

The International Residential Code requires all habitable rooms to have a net exterior glazed area equal to at least 8 percent of their floor area. The use of natural light to provide interior illumination and the provision of views

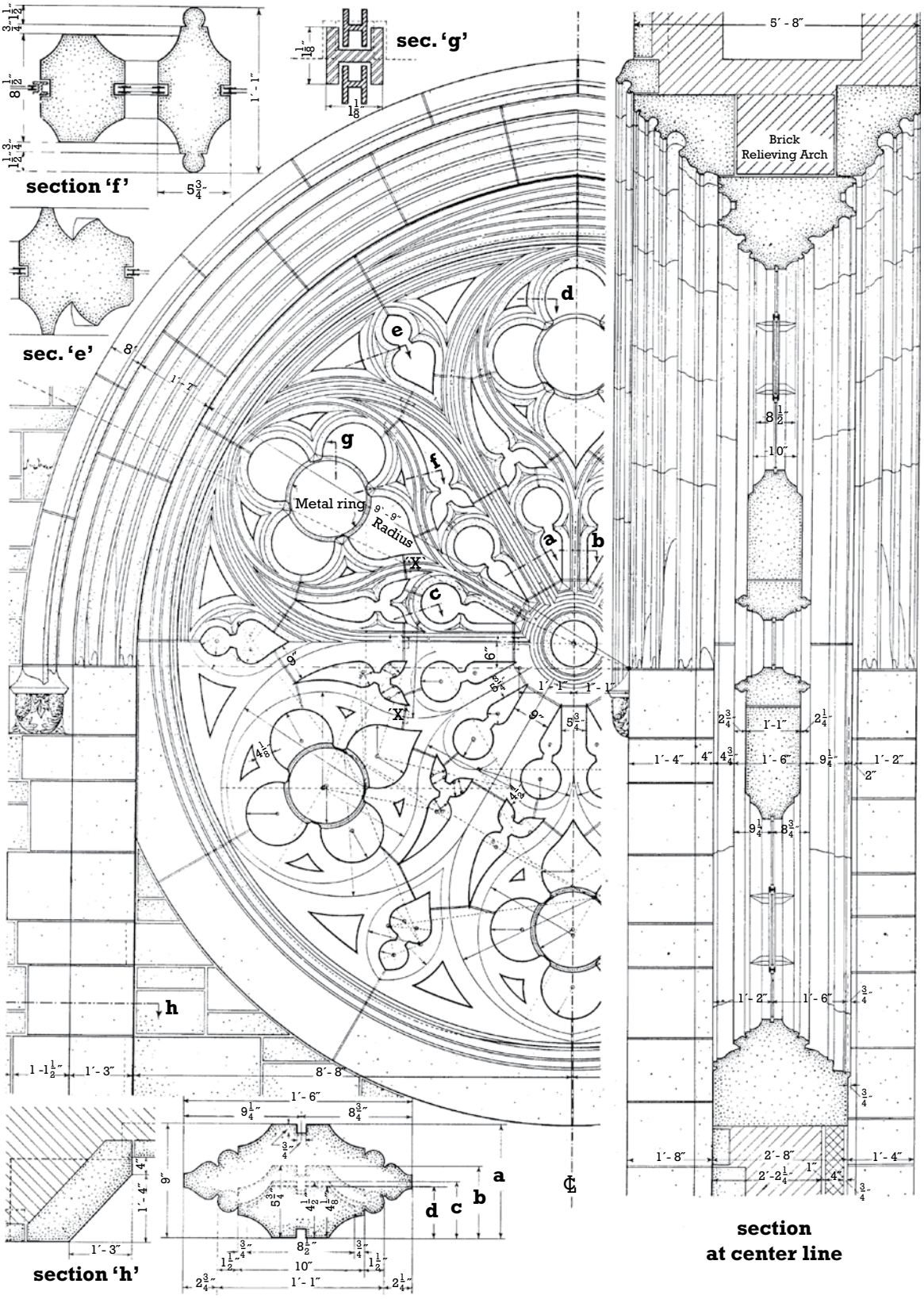


Figure 18.31
Limestone and metal mullions for a Gothic church window. *(Courtesy of Indiana Limestone Institute.)*

FIGURE 18.32
Leaded stained glass in the Robie House, Chicago, 1906. *(Architect: Frank Lloyd Wright.)*

to the exterior for building occupants are recognized components of healthy, energy-efficient buildings and are encouraged by sustainable design programs.

Other regulatory concerns related to the use of glass in buildings have already been discussed: Vertical glass that is subject to human impact must be of a type that does not break into dangerous shards. Overhead glass, if it breaks, must not fall onto building occupants. Glass in fire-rated walls, doors, and windows must meet standards to ensure that it remains sufficiently intact and performs as needed during a building fire.

Lastly, energy conservation codes limit the loss of heat or cooling through windows and other glazed openings, either by limiting the area of glazing or by mandating minimum levels of resistance to heat flow by the glass and its framing system.

MasterFormat Sections for Glass and Glazing

08 44 00	**CURTAIN WALL AND GLAZED ASSEMBLIES**
08 44 23	Structural Sealant Glazed Curtain Walls
08 44 26	Structural Glass Curtain Walls
08 81 00	**GLASS GLAZING**
08 81 26	Exterior Glass Glazing
08 83 00	**MIRRORS**
08 84 00	**PLASTIC GLAZING**
08 88 00	**SPECIAL FUNCTION GLAZING**
08 88 13	Fire-Resistant Glazing
08 88 23	Cable Suspended Glazing
08 88 36	Switchable Glass
08 88 53	Security Glazing

Key Terms

crown glass
cylinder glass
punty
plate glass
drawn glass
float glass
flat glass
lehr
glazing
glazier
light, lite
annealed glass
single-strength glass
double-strength glass
heat-treated glass
quenching
tempered glass, fully tempered glass
heat-strengthened glass
laminated glass
interlayer
polyvinyl butyral (PVB)
safety glazing
hazardous locations
CPSC 16 CFR Part 1201
Category II glazing
Category I glazing
ANSI Z97.1
fire-rated glass
fire-protection-rated glazing
fire-resistance-rated glazing
damage weighted transmittance (Tdw, ISO-CIE Tdw, Tdw-ISO)
fritted glass
frit
spandrel glass
visible light transmittance (VT)
tinted glass
solar heat gain coefficient (SHGC)
light to solar gain (LSG) ratio
reflective coated glass, solar control glass
single glazing
double glazing
triple glazing
insulating glass unit (IGU)
edge spacer, spline
desiccant
dual seal spacer
warm edge spacer
U-Factor
vacuum-insulated glazing
low-emissivity (low-e) coating
glass surface number
low-iron glass
antireflective glass
silk-screened glass
digitally printed glass
self-cleaning glass
chromogenic glass
thermochromic glass
photochromic glass
electrochromic glass, switchable glass
chemically strengthened glass
mirror glass
patterned glass
radiation-shielding glass
photovoltaic glass
stained glass
colored glass
art glass
acrylic glazing
polycarbonate glazing
cellular polycarbonate glazing
glass-fiber-reinforced polyester (fiberglass) glazing
ethylene tetrafluoroethylene (ETFE)
glazing stop
glazing compound
exterior glazed
interior glazed
setting block
bite
glazing bead
weep
dry glazing component
wet glazing component
solid glazing tape
butt-joint glazing
flush glazing
pressure bar (pressure plate)
structural glazing
structural glazing adhesive
structural silicone sealant
acrylic foam structural glazing tape
point-supported glazing
glass mullion system
suspended glazing system

Review Questions

1. What are the advantages of float glass over drawn glass? Over plate glass?

2. Name two situations in which you might use each of the following types of glass: (a) annealed glass, (b) tempered glass, (c) laminated glass, (d) low-e coated glass, (e) plastic glazing.

3. What are the design objectives for a large-lite glazing system?

4. In what ways does a typical building code regulate the use of glass and why?

5. What is a low-e coating, and what are its benefits?

Exercises

1. Examine the ways in which glass is mounted in several actual buildings and sketch a detail of each. Explain why each detail was used in its situation and why you agree or disagree with the choice of detail used.

2. Discuss the role of glass that faces each of the principal directions of the compass in adding solar heat to an air-conditioned office building in summer. How should windows be treated on each of these facades to minimize summertime solar heat gain?

Selected References

The most current information on glass will be found in manufacturers' product literature, available either in hard copy or on the Internet.

Glass Association of North America. *GANA Glazing Manual*. Topeka, KS, updated regularly.

This handbook summarizes current practice in the production and use of glass in buildings.

Schittich, Christian et al. *Glass Construction Manual*. Munich, Birkhauser Verlag, 2007.

This is a beautifully produced and comprehensive treatment of modern uses of glass in architecture, including the material properties of glass, glazing and building energy consumption, and the details of glazing systems.

Websites

Glass and Glazing

Cardinal Glass Industries: www.cardinalcorp.com

Corning Museum of Glass: www.cmog.org

Glass Association of North America (GANA): www.glasswebsite.com

Nathan Allan Glass Studios: www.nathanallan.com

National Glass Association: www.glass.org

Pilkington: www.pilkington.com/en/us

TGP (fire-rated glass and framing): www.fireglass.com

Vitro Architectural Glass: www.vitroglazings.com/en-US

Whole Building Design Guide, Glazing: www.wbdg.org/guides-specifications/building-envelope-design-guide/fenestration-systems/glazing

CASE STUDY: Skating Rink at Yerba Buena Gardens

DESIGN ARCHITECT: Santos Prescott and Associates

EXECUTIVE ARCHITECT: LDA Architects

STRUCTURAL ENGINEER: Johnson and Neilsen/SOH&A

The project concept was to make the skating rink at Yerba Buena Gardens, San Francisco, a great urban room, intimately connected with its civic surroundings. Early in design, as part of its strategy to achieve this goal, architect Santos Prescott and Associates envisioned the north wall of the rink constructed entirely of glass. This would maximize the rink's connection to the neighboring outside garden and capitalize on views of the city skyline beyond. Finding an economical and elegant solution to the design and construction of this curtain wall became one of the essential ingredients in realizing the project (Figure A).

As the design developed, translucent glazing panels were proposed for the remaining sides of the rink enclosure to provide balanced natural illumination. As a consequence, Santos Prescott was now looking for a glazing system that could accommodate both 2¾-inch-thick translucent panels as well as standard 1-inch clear glazing for the south wall. As the building continued to take shape, additional criteria were established:

- At 30 feet in height, the south wall was too tall for the aluminum curtain wall to span on its own. A structural steel frame would be required behind the curtain wall to provide support against wind loads.
- Once the decision was made to fully support the curtain wall, structural requirements for the mullion system itself became minimal. This freed the architect to choose a relatively simple mullion profile based primarily on its ability to accommodate the glazing materials of varying thicknesses.
- To maximize transparency and fit the curtain wall within the spacing of the roof supports, a mullion grid 11 feet 3 inches wide × 5 feet high was established. These dimensions were approaching the upper size limits for sealed insulating glass units. However, pushing for larger glass units also permitted the least number of curtain wall mullions and steel backup elements to be used.

Once a curtain wall system had been selected, work proceeded in close coordination with the structural engineer to develop the steel backup structure in greater detail (Figure B). Still striving for transparency, the goal was to find the slenderest support elements possible. Because deflection under wind load was the limiting factor in the design, a tube section was selected for its efficient sectional properties, and final sizes were determined: 3 × 8 × ½ inches for the vertical tubes and 3 × 3 × ⅜ inches for the horizontal tubes.

In the construction documents, the aluminum curtain wall and steel backup assembly were detailed (see Figure C) and its various components were specified. In the case of the aluminum mullion system, the specification (see excerpt) delegated the final engineering of this part of the assembly to its supplier. Performance criteria included resistance to structural loads, accommodation of movement, allowance for dimensional tolerances within the supporting elements, allowance for thermal expansion and contraction, and more.

Also included in the specification were requirements for the supplier to submit shop drawings and product information describing in detail the proposed curtain wall components and their attachment to the structural backup. Later in the project, these documents were reviewed by the general contractor, the architects, and the structural engineer. This review ensured that the proposed system indeed met the specified requirements and that the various parts of the curtain wall/glazing/structural system would come together as intended.

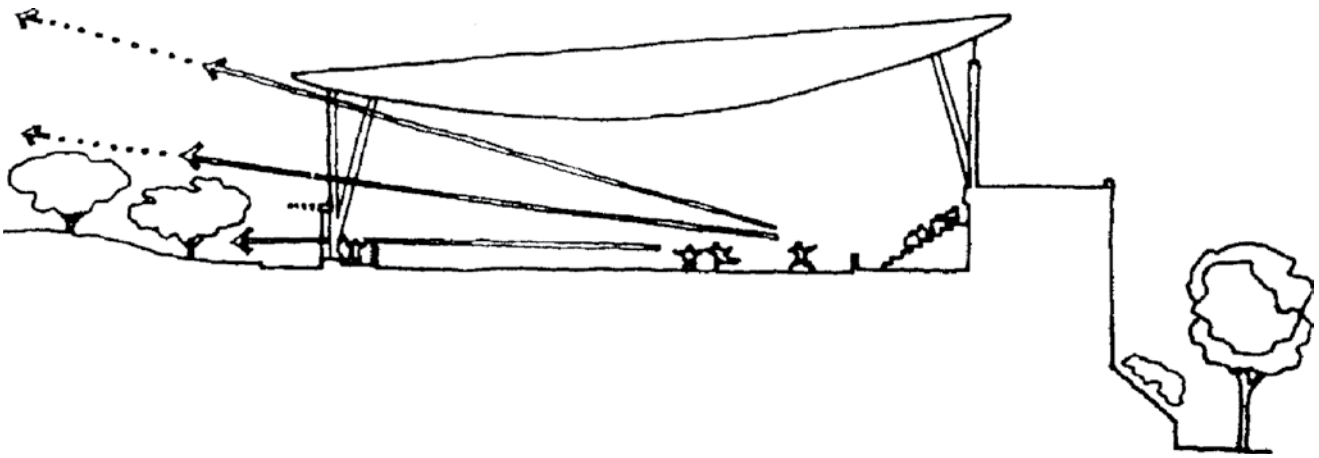


FIGURE A
Concept diagram.

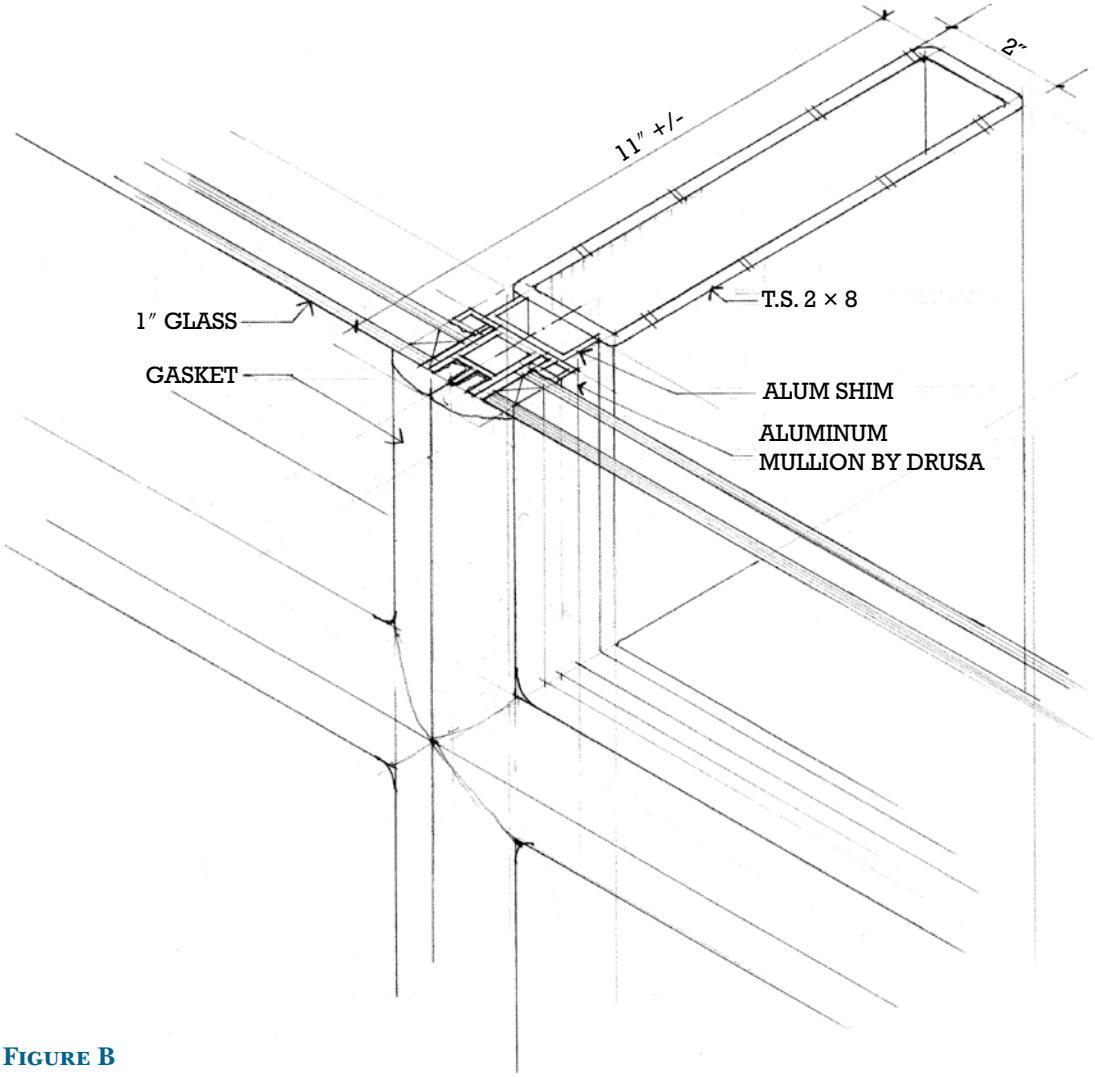


Figure B
Schematic study of the curtain wall and steel support assembly.

SECTION 08 44 13

GLAZED ALUMINUM CURTAIN WALLS

PART 1—GENERAL

1.03 PERFORMANCE REQUIREMENTS

A. General: Provide glazed aluminum curtain wall systems, including anchorage, capable of withstanding, without failure, the effects of the following:

1. **Structural loads**
2. **Movements of supporting structure including, but not limited to, story drift, twist, column shortening, long-term creep, and deflection from uniformly distributed and concentrated live loads**
3. **Dimensional tolerances of building frame and other adjacent construction**
4. **Thermal expansion and contraction**

During the construction phase, a change was required. While preparing shop drawings, the curtain wall installer uncovered potential difficulties in attaching the curtain wall to the steel structure. When erection tolerances for the steel tubes were taken into consideration, it became apparent that it might not be possible to position the tubes with sufficient precision to meet the fastening requirements of the curtain wall. This problem was exacerbated by the ½-inch-thick sidewalls of the vertical steel tubes, which reduced the allowable area for fasteners on the face of the tubes to a narrow central band. At this relatively late stage in the project, the decision was made to switch to a 4-inch-wide tube with a thinner sidewall to provide a wider target area for fasteners (Figure D). In the end, the change had little if any noticeable visual impact (Figure E).

This example illustrates how a successful project outcome depends on good communication among the various team members throughout the design and construction of the project, and how even seemingly minor technical considerations can affect essential aspects of a project's design.

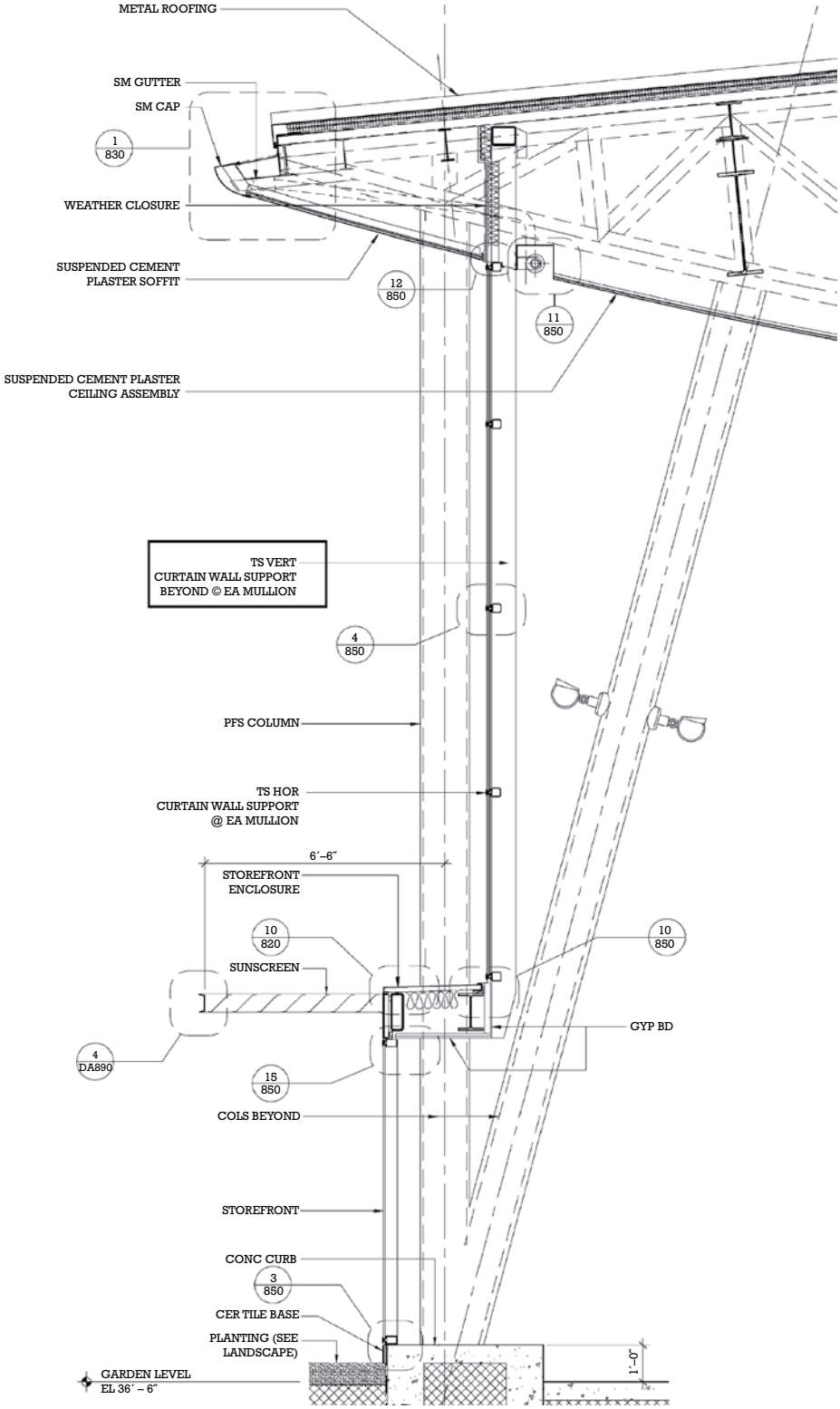


FIGURE C
Wall section from the construction drawing set.

Special thanks to Santos Prescott and Associates and Bruce Prescott, principal, for assistance with the preparation of this case study.

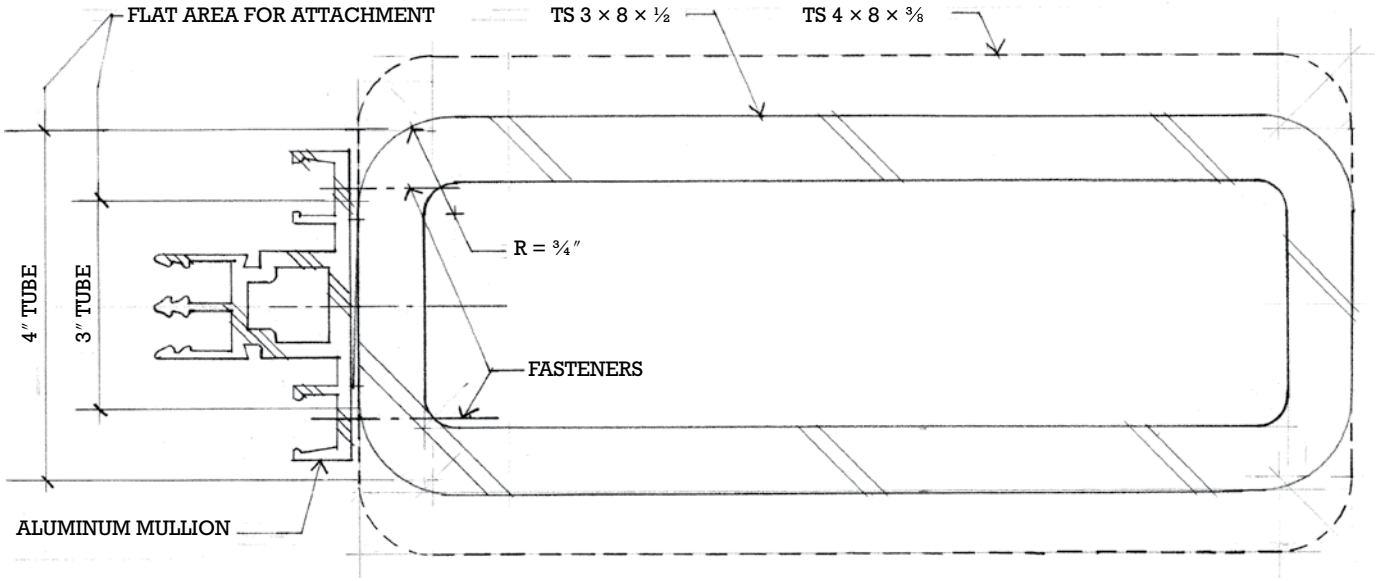


FIGURE D
Detail study of the curtain wall attachment to tube steel.

FIGURE E
Interior view of the completed building.

POPLAR HALL

19

Windows and Doors

- **Windows**
  - Types of Windows
  - Window Frames
  - Plastics in Building Construction
  - Muntins
  - Glazing
  - Installing Windows
  - Sustainability and Windows and Doors
- **Doors**
  - Wood Doors
  - Steel Flush Doors
  - Fiberglass Doors
  - Fire Doors
  - Egress Doors and Accessible Doors
  - Door Hardware
  - Installing Doors
- **Other Window and Door Requirements**
  - Safety Considerations in Windows and Doors
  - Structural Performance and Resistance to Wind and Rain
  - Thermal Performance
  - Acoustic Isolation
  - Impact Resistance
  - Blast Resistance

High-performance windows and glazing contribute to a LEED Gold rating for the University of Washington's Poplar Hall. *(Architect: Mahlum. Photo by Joseph Iano.)*

Doors and windows are very special components of walls. Doors permit people, goods, and sometimes even vehicles to pass through walls. Windows allow for simultaneous control of the passage of light, air, heat, and sight through walls. Windows and doors, in addition to performing these important functions, play a large role in establishing the character and personality of a building, much as our eyes, nose, and mouth play a large role in our personal appearance. At the same time, windows and doors are the most complex, expensive, and potentially troublesome parts of a wall. To achieve satisfactory results, the experienced designer exercises great care and wisdom in the selection of doors and windows and in the specification of their installation.

Windows

The word *window* is thought to have originated in an old English expression that means "wind eye." The earliest windows in buildings were open holes through which smoke could escape and fresh air could enter. Devices were soon added to the holes to give greater control: hanging skins, mats, or fabric to regulate airflow; shutters for shading and to keep out burglars; translucent membranes of oiled paper or cloth, and eventually of glass, to admit light while preventing the passage of air, water, and snow. When a translucent membrane was eventually mounted in a moving sash, light and air could be controlled independently of each other. With the addition of woven insect screens, windows permitted air movement while keeping out mosquitoes and flies. Further improvements followed over the centuries. A typical window today is an intricate mechanism with many layers of control: curtains, shade or blind, sash, glazings, insulating airspace, low-emissivity and other coatings, insect screen, weatherstripping, and perhaps a storm sash or shutters.

Windows were formerly made on the construction site by highly skilled carpenters, but today nearly all of them are produced in factories. The primary reasons for factory production are higher production efficiency, lower cost, and, importantly, better quality. Windows must be made to a high standard of precision if they are to operate easily and maintain a high degree of weathertightness for many years. In cold climates especially, a loosely fitted window and a frame that is highly conductive of heat will significantly increase fuel consumption for a building, cause noticeable discomfort to the occupants, and condense large quantities of water that will stain and decay materials in and around the window.

Types of Windows

Figure 19.1 illustrates in diagrammatic form the window types used most commonly in residential buildings, and Figure 19.2 shows additional types that are found largely in commercial and institutional buildings. *Fixed windows* are the least expensive and the least likely to leak air or water, because they have no operable components. *Single-hung* and *double-hung windows* have one or two moving *sashes*, which are the frames in which the glass is mounted (Figure 19.3). The sashes slide up and down in tracks that are part of the window frame. In older windows, the sashes were held in position by cords and counterweights, but today's double-hung windows rely on systems of springs to counterbalance the weight of the sashes. A *sliding window* is essentially a single-hung window on its side and shares with single-hung and double-hung windows the advantage that tracks in the frame hold the sashes securely along two opposite sides. This inherently stable construction allows single-hung, double-hung, and sliding windows to be designed in an almost unlimited range of sizes and proportions. It also allows the sashes to be more lightly built than those in *projected windows*, a category that includes principally *casement, awning, hopper, inswinging*, and *pivot windows*. All projected windows have sashes that rotate outward or inward from their frames and therefore must be stiff enough to resist wind loads while being supported only along one side.

With the exception of the rare *triple-hung window*, no window with sashes that slide can be opened to more than half of its total area. By contrast, many projected windows can be opened to almost their full area. Projecting casement windows assist in catching passing breezes and inducing ventilation through the building. They are generally narrow in width but can be joined to one another and to sashes of fixed glass to fill wider openings. Awning windows can be broad but are not usually very tall. They have the advantages of providing protection from water during a rainstorm, even when open, and of lending themselves to a building-block approach to the design of window walls (Figure 19.4). Hopper windows are more common in commercial buildings than in residential ones. Like awning windows, they will admit little or no rainwater if left open during a rainstorm. *Tilt/turn windows* (not illustrated) are a type of projected window with clever, concealed hardware that allows each

FIGURE 19.1
Basic window types.

Top-Hinged Inswinging

Side-Hinged Inswinging

Pivoting

FIGURE 19.2
Additional window types that are used mainly in larger buildings.

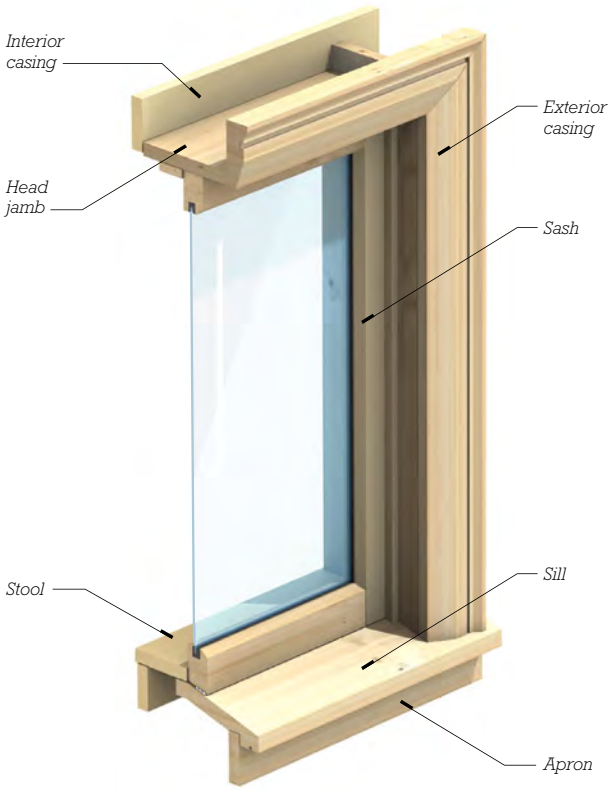


FIGURE 19.3
Basic window nomenclature follows a tradition that has developed over many centuries. The *jamb* consists of the *head jamb* across the top of the window and the *side jamb* to either side. In practice, the head jamb is usually referred to simply as the *head* and the side jambs as jambs. The *sill* frames the bottom of the opening on the exterior side, and the *stool* does the same on the interior. *Interior casings* and *exterior casings* cover the gaps between the jambs and the rough opening, and *aprons* do the same below the sill and stool.

sash to operate both as a side-hinged inswinging window and as a hopper. Window types that are used almost exclusively in commercial and institutional work include horizontally and vertically *pivoting windows* and *top-hinged inswinging windows.*

Most tall buildings do not provide operable windows, due to the complexity of balancing varying air pressures on the outside of the building with those of the internal air-handling system. These make it difficult to maintain steady, comfortable air temperatures and speeds within the building. However, with proper design (and in appropriate climates), operable units can be part of a natural ventilation strategy that provides comfortable airflows in place of a mechanical air conditioning system. On tall buildings, inswinging window types may be preferred, as they are less vulnerable to damage by high winds. For safety reasons, such windows are be fitted with devices that limit the extent to which they can be opened.

A projected window is usually provided with synthetic rubber weatherstripping that compresses snugly around the edges of the sash when the window is closed. Single-hung, double-hung, and sliding windows

FIGURE 19.4
Awning and fixed windows in coordinated sizes offer the architect the possibility of creating patterned walls of glass. *(Courtesy of Marvin Windows and Doors.)*

must rely on brush-type or very low-modulus (highly flexible) weatherstripping that does not exert so much friction as to make operation of the sash difficult. However, these weatherstripping types also may not seal as tightly and are subject to greater wear over the life of the windows. As a result, projected windows are frequently more resistant to air leakage than windows that slide in their frames.

Glazed units installed in roofs are specially constructed and flashed to remain watertight in their sloping or horizontal orientation. *Skylights* may be either fixed or operable (*venting skylight*). The term *roof window* is also sometimes applied to venting skylights; at other times, it is applied more narrowly only to window-like units that include some kind of inward rotation capability, making glass cleaning easier.

Large glass doors (which are most often supplied by window manufacturers) may slide in tracks or swing open on hinges (Figure 19.1). The hinged *French door* opens fully (either inward or outward) and, with its arms flung wide, is a more welcoming type of door than the *sliding door*, but it cannot be used to regulate airflow through the room unless it is fitted with a doorstop that can hold it securely in an open position. The French door is prone to air leakage along its seven separate edges, which must be carefully fitted and weatherstripped. The *terrace door*, with only one operating door, minimizes this problem but, like the sliding door, can open to only half its area.

Insect screens may be mounted only inside the sash in casement and awning windows (because the sash swings outward). Screens are usually positioned to the exterior side of other window types. Sliding patio doors and terrace doors have exterior sliding screens, and French doors require a pair of hinged screen doors that must swing in the opposite direction of the doors themselves. Pivoting windows cannot be fitted with insect screens.

Glass must be washed at intervals if it is to remain transparent and attractive. Inside surfaces of glass are relatively easy to reach. Outside surfaces are often harder to reach, requiring ladders, scaffolding, or window-washing platforms that hang from the top of the building on cables. Accordingly, most operable windows are designed to allow washing of the outside glass surface from inside the building. Casement and awning windows are usually hinged in such a way that there is sufficient space between the hinged edge of the sash and the frame when the window is open to allow one's arm to reach the outer surface of glass. Double-hung and sliding windows are often designed to allow sashes to be rotated or tilted out of their tracks to allow easy access to exterior glass (Figure 19.11). Inward-swinging window types naturally expose their outer glass surfaces to the interior when opened.

As seen in many of the following figures, windows and glass doors may also be combined side by side or stacked vertically to create larger glazed areas with any of a great variety of fixed and operable component configurations.

Window Frames

Wood

Wood is the traditional frame material for windows. It is a fairly good thermal insulator, changes size relatively little with changes in temperature, and, if free of knots, is easily worked and consistently strong. In service, though, wood shrinks and swells with changing moisture content and requires repainting every few years. When wetted by weather, leakage, or condensate, *wood windows* are subject to decay, though their resistance to decay can be improved with preservative treatments. Knot-free wood is becoming rare and expensive, so composite wood products are increasingly used. These include lumber made of short lengths of defect-free wood finger-jointed and glued together, oriented strand lumber, and laminated veneer lumber. These materials, although functionally satisfactory, are not attractive, so they are covered with wood veneer on the interior and clad with plastic or aluminum on the exterior (Figures 19.5 and 19.6). Such *clad wood windows* account for the largest share of the market for wood-framed windows.

Figure 19.5
Cutaway sample of an aluminum-clad wood-framed window. *(Courtesy of Marvin Windows and Doors.)*

Figure 19.6
Large double-hung wood windows and a triangular fixed window bring sunlight and views. *(Courtesy of Marvin Windows and Doors.)*

Aluminum

Aluminum, when used in window construction, is strong, easy to form and join, and, in comparison to wood, much less vulnerable to moisture damage. The extrusion process by which aluminum sections are formed results in shapes with crisp, attractive profiles. Durable factory finishes eliminate the need for periodic repainting after installation.

However, aluminum conducts heat rapidly. Unless the frame is constructed with a *thermal break* made of plastic or synthetic rubber components to interrupt the flow of heat through the metal, the window will be thermally inefficient and at risk of condensate, and sometimes even frost, forming on interior frame surfaces during cold winter weather. *Aluminum windows* are also more costly than wood or plastic windows. The majority of commercial and institutional windows, as well as many residential windows, are framed with aluminum (Figures 19.7, 19.8, and 19.9). Aluminum frames are usually anodized or permanently coated, as described in Chapter 21.

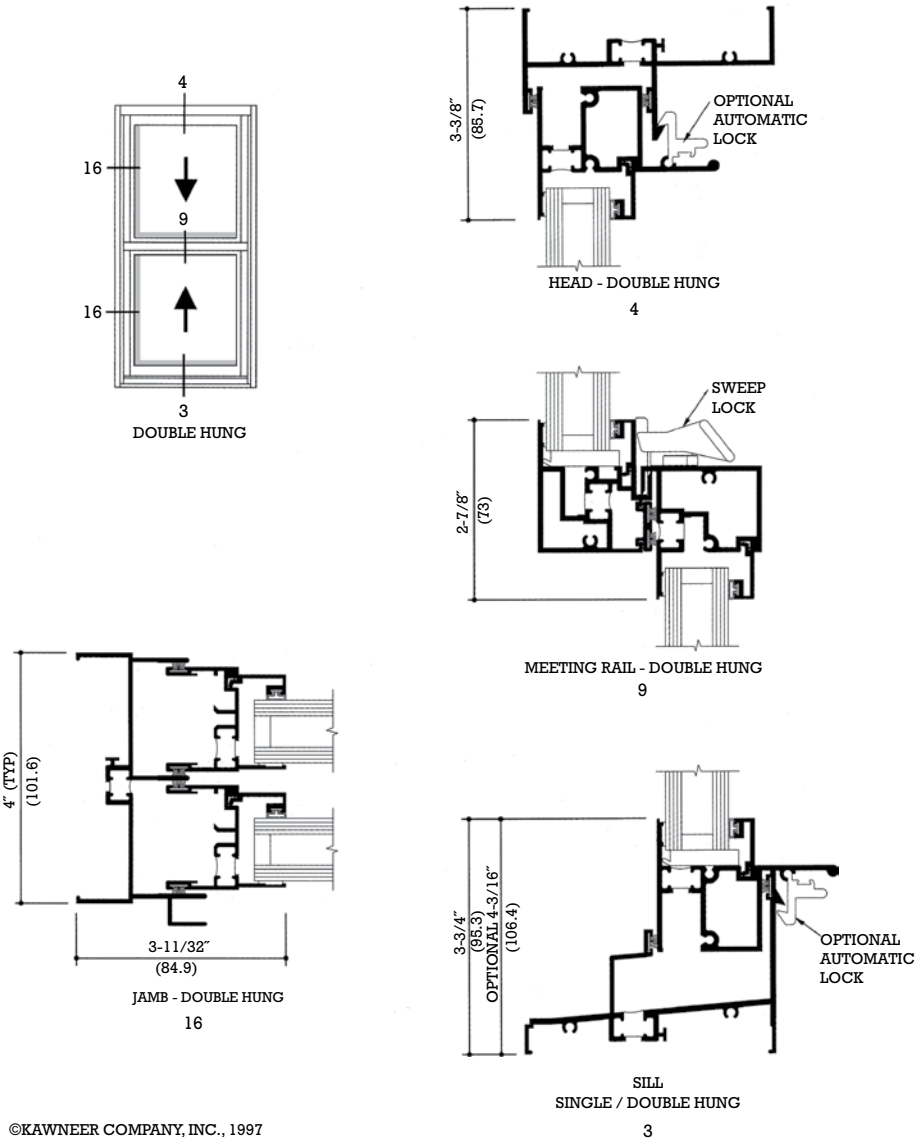


FIGURE 19.7

The details of this commercial-grade double-hung aluminum window are keyed to the numbers on the small elevation view at the upper left. Cast and debridged thermal breaks, which are shown on the drawings as small white areas gripped by a "claw" configuration of aluminum on either side, separate the outdoor and indoor portions of all the sash and frame extrusions. Pile weatherstripping seals against air leaks at all the interfaces between sashes and frame. For help in understanding the complexities of aluminum extrusions, see Chapter 21. *(Courtesy of Kawneer Company, Inc.)*

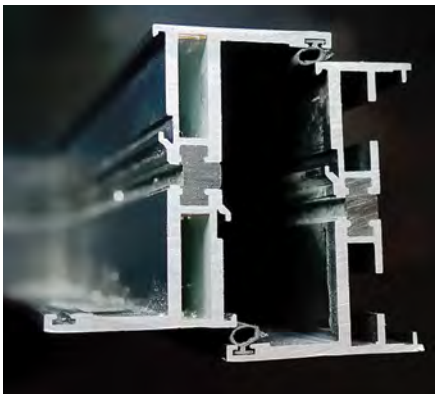


FIGURE 19.8

A standard cast and debridged plastic thermal break in an aluminum window frame. *(Photo by Joseph Iano.)*

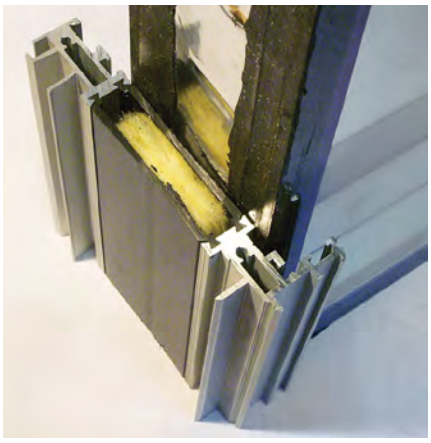


FIGURE 19.9

A highly thermally efficient polyamide plastic thermal break filled with fibrous insulation. The accompanying glazing consists of two outer lites of ¼-inch (6-mm) glass and two inner plastic films. The exterior lite and the innermost film both have low-emissivity coatings. The metal foil vapor barrier in the warm edge spacer is also visible. This window can achieve an overall thermal performance of approximately U-0.13 (U-0.75 metric). For comparison with other common window types, see Figure 19.17. *(Photo by Joseph Iano.)*

Plastics

Plastic window frames account for roughly two-thirds of all windows sold in the U.S. residential market. Plastic windows never need painting, and they are fairly good thermal insulators. They also cost less than most wood or clad wood windows. The disadvantages of plastics are that they are not as stiff or strong as other window materials and they have very high coefficients of thermal expansion. The most common material for plastic window frames is polyvinyl chloride (PVC, vinyl), which is formulated from PVC itself along with heat and UV-stabilizers (Figures 19.10, 19.11, and 19.12). In larger window units, the frames may be reinforced with steel or aluminum inserts for greater strength and stiffness.

Glass-fiber-reinforced plastic (GFRP) windows, frequently referred to as *fiberglass windows*, are produced by a process of *pultrusion*: Continuous lengths of glass fiber are pulled through a bath of plastic resin, usually polyester, and then through a shaped, heated die in which the resin hardens. The resulting sash pieces are strong, stiff, relatively low in thermal expansion, and highly UV-resistant. Like PVC, they are fairly good thermal insulators. However, GFRP windows are more expensive than those made of wood or plastic.

The thermal performance of both vinyl and GFRP window frames is sometimes enhanced with foam insulation inserted or injected into the hollow spaces within the frame sections.

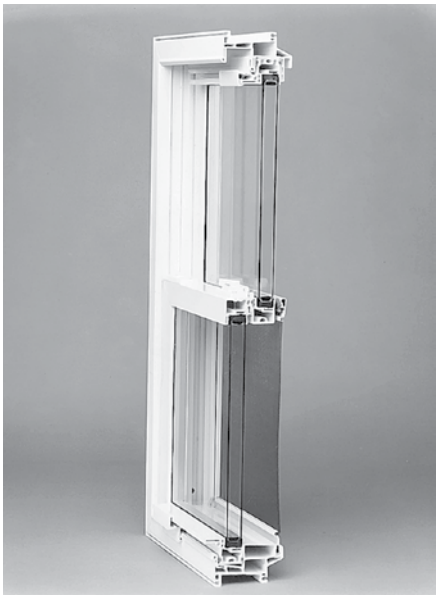


FIGURE 19.10
Cutaway sample of a plastic double-hung window with double glazing and an external half-screen. *(Courtesy of Vinyl Building Products, Inc.)*

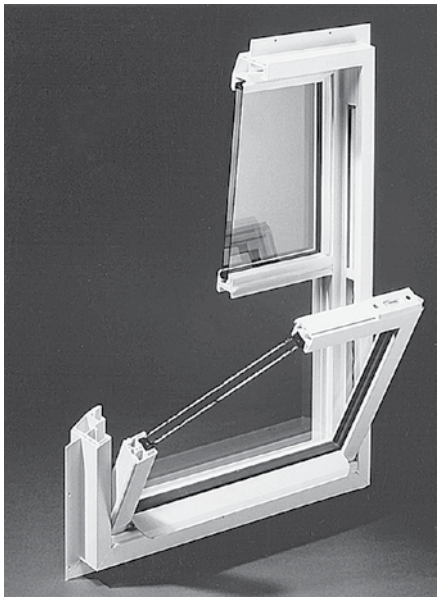


FIGURE 19.11
For ease of washing the exterior surfaces of the glass, the sashes of this plastic window can be unlocked from the frame and tilted inward. *(Courtesy of Vinyl Building Products, Inc.)*

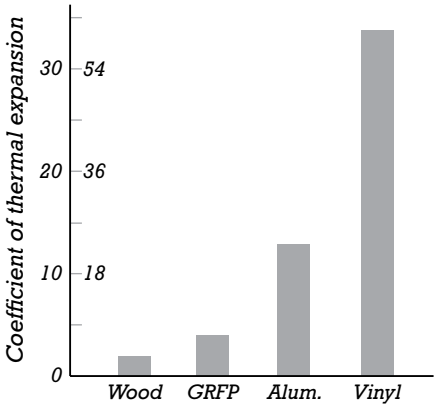


FIGURE 19.12
A comparison of the coefficients of thermal expansion of wood, glass-fiber-reinforced plastic (GFRP), aluminum, and vinyl. Vinyl expands 15 times as much as wood, 8 times as much as GFRP, and 3 times as much as aluminum. Units on the graph are in./in./°F × 10^{-6} on the left of the vertical axis and mm/mm/°C × 10^{-6} on the right.

Plastics in Building Construction

Plastics may be loosely defined as giant molecules (called polymers and copolymers) made up of large numbers of smaller, repetitive chemical units. Such molecular chains occur naturally: for example, in the cellulose from which tree cells are structured. The first synthetic plastics were formulated in the 19th century, and the development of modern plastic materials began in earnest in the 1930s. In the United States today, more than 50 billion tons (45 billion tonnes) of plastic resins are produced annually, and the construction industry is the second largest consumer of products made from those resins.

Synthetic plastics are manufactured largely from organic molecules obtained from oil, natural gas, and coal. Most are based on carbon chains, except for the silicones, which are structured around silicon (Figure A). *Synthetic rubber* compounds, also called *elastomers*, are usually classified separately from plastics, although chemically they are similar.

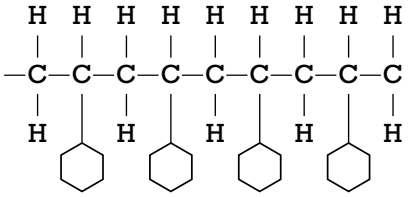
A *polymer* is composed of many identical chemical units or *monomers*. PVC, for example, is a polymer consisting of long chains of chloride monomers. A *copolymer* consists of repeating patterns of two or more monomers. High-impact polystyrene is a copolymer made up of both polystyrene and polybutadiene.

The molecular structure of a polymer or copolymer bears an important relationship to its physical properties. A high-density polyethylene molecule, for instance, is a long, compact, single chain containing up to 200,000 carbon atoms. Low-density polyethylene has a branching structure that does not pack together as tightly as the single chain.

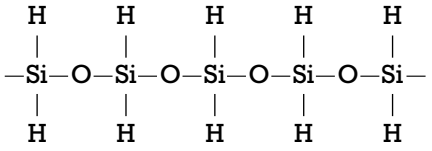
There are two broad classes of plastics. *Thermoplastic* plastics may be softened by reheating at any time after their manufacture. Upon cooling, they regain their original properties. *Thermosetting* plastics have a molecular structure that is strongly *crosslinked* in three dimensions. They cannot be remelted after manufacture. Thermosetting plastics are generally more heat-resistant and chemically stable than thermoplastics.

Modifiers are added to plastics to change their properties or reduce their cost. *Plasticizers* impart flexibility and softness. *Stabilizers* improve resistance to the deteriorating effects of sunlight, heat, oxygen, and electromagnetic radiation. *Fillers*, such as talc or marble dust, are added to reduce cost or improve toughness or resistance to high temperatures. *Extenders* are waxes or oils that add bulk. *Reinforcing fibers* of glass, metal, carbon, or minerals can increase strength, impact resistance, stiffness, abrasion resistance, hardness, and other mechanical properties. *Flame retardants* are often introduced into plastics that are destined for interior use in buildings. Color can be added to plastics with dyes or pigments.

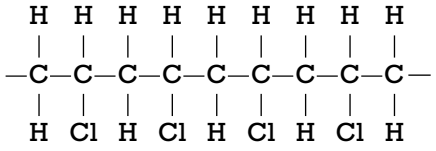
The plastics used in buildings range from high-density structural components to the lightweight cellular foams used for thermal insulation. They include soft, pliable sheets used for roofing membranes and flashings and hard, rigid plastics used for plumbing pipes. Glazing sheets are made from highly transparent plastics, whereas most plastics manufactured for other purposes are opaque.



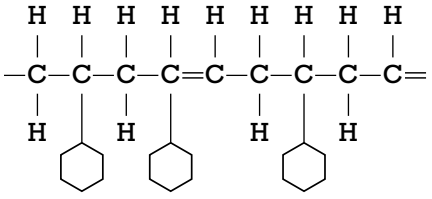
Polystyrene.



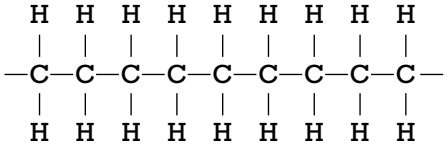
A silicone.



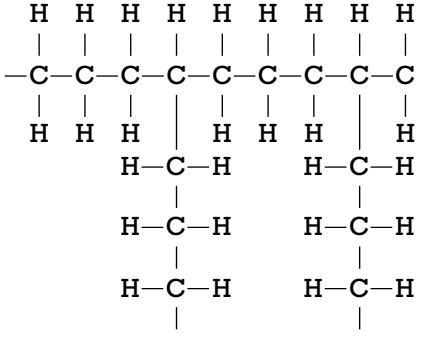
Polyvinyl chloride (PVC).



High-impact polystyrene.



High-density polyethylene.



Low-density polyethylene.

Figure A

Plastics in Building Construction (continued)

Liquid plastics are major ingredients of many paints and protective coatings. Plastics show up also in *composites*, in which they are teamed with nonplastic materials: *laminates* of paper and melamine formaldehyde, used for countertops and facings; sandwiches such as foam-core and plywood structural insulated panels; and mixes of plastics with particulate materials, such as polyester concrete (stone aggregates cemented with a polyester binder rather than portland cement) and particleboard (wood chips and phenolic resins).

Plastics are given form through any of an almost endless list of processes. *Extrusion* manufactures long shaped sections by forcing the plastic through a shaped die. Pultrusion, used for certain fiber-reinforced products, is much the same as extrusion, except that the section is pulled through the die rather than pushed. A host of *molding* processes cast plastic into shaped cavities to give it form. Films and sheets can be made by casting plastic onto a chilled roller or a chilled moving belt. Some plastic sheet products and many plastic laminates are produced by *calendaring*, a process in which a material or a sandwich of materials is pressed first through hot rollers, then cold rollers.

Thermoplastic sheets may be further formed by heating them and pressing them against shaped dies. The pressing force may be furnished mechanically by a

Some Plastics Used in Construction

Acrylonitrile-butadiene styrene terpolymer (ABS)	Piping, preformed shower stalls; TP[a]
Alkyd	Coatings; TS[b]
Epoxy	Adhesives, coatings, binders; TS
Ethylene tetrafluoroethylene (ETFE)	Thin glazing membranes, roofing; TP
Polybutene	Sealants, tapes; TP
Polycarbonate	Glazing; TP
Polyester	Reinforcing fabrics and fibers; TS
Polyethylene	Vapor retarders, piping; TP
Polyisocyanurate	Insulating foam; TS
Polymethyl methacrylate (acrylic)	Glazing, coatings, roofing, adhesives; TP
Polypropylene	Reinforcing fibers; TP
Polystyrene	Insulating foam; TP
Polytetrafluorethylene (PTFE, Teflon)	Sliding bearings, washers, pipe thread tape; TP
Polyvinyl chloride (PVC, vinyl)	Piping, conduit, siding, window frames, flooring, roofing; TP
Polyvinylidene fluoride (PVDF)	Coatings; TP
Thermoplastic Polyolefin (TPO)	Roofing; TP

Some Synthetic Rubbers Used in Construction

Ethylene propylene diene monomer (EPDM)	Roofing, flashing; TS
Isobutylene isoprene copolymer (butyl rubber)	Flashing, waterproofing; TS
Polychloroprene (neoprene)	Gaskets, flashing; TS
Polysiloxanes (silicone rubber)	Sealants, adhesives, flashing; TS
Polyurethane	Sealants, coatings, insulting foam, flooring; TS or TP
Silyl-terminated polymer	Flashing, air and water barrier membrane; TS
Styrene butadiene rubber (SBR)	Rubber flooring; TS

[a]TP: Thermoplastic.

[b]TS: Thermoset.

matching die or by air pressure. If compressed air pushes the plastic into the die, the process is called *blow forming*. In *vacuum forming*, a pump draws the air from between the heated plastic sheet and the die, and atmospheric pressure does the rest.

Many plastics are amenable to machining processes—sawing, drilling, milling, planing, turning, sanding—like those used to shape wood or metal. Thermoplastic plastics can be joined with heat or solvents that weld or fuse them together as a single piece. The crosslinked chemistry of thermoset plastics does not permit welding, so these materials must be joined with adhesives. Denser, harder plastics may be joined mechanically with screws or bolts. Many plastic products are designed with ingenious snap-together features so that they can be joined without fasteners.

As a group, plastics exhibit some common advantages and some common problems when used as building materials. Among the advantages, plastics are low in density; they are often cheaper than other materials that will do the same job; they have good surface and appearance qualities; and, because their molecules are made to order for each end use, they can often offer a more optimal solution to a building problem than other materials. Plastics generally are little affected by water or biological decay, and they do not corrode. They tend to have low thermal and electrical conductivity. Many have high strength-to-weight ratios. Most plastics are essentially impermeable to water and water vapor. Many are very tough and resistant to abrasion.

Their disadvantages are also numerous. Synthetic plastics are derived chiefly from oil, coal, and natural gas, all nonrenewable resources. There are also environmental and health concerns with some plastics and their manufacturing processes.

For example, polyvinyl chloride (PVC), a material with many applications in building construction, has become associated with a range of human health and environmental hazards: A key ingredient in the manufacture of PVC is the toxic gas chlorine. The manufacturing process also generates dioxin and PCBs (polychlorinated biphenyls), compounds associated with cancer and neurological damage. Hazardous heavy metals and phthalates, added as plasticizers, stabilizers, and pigments, can leach out of the material and find their way into human or animal biosystems. And when PVC is burned in municipal or medical waste incinerators, dioxins and other harmful compounds are released into the atmosphere or remain in the ash left behind. As a consequence, PVC is included on both the Living Building Challenge Red List and the Cradle to Cradle Banned List of Chemicals. In an effort to mitigate such concerns, the PVC manufacturing industry is improving its manufacturing processes, searching for substitutes for the most harmful ingredients, and instituting reuse or recycling programs to divert PVC from disposal in landfills or incineration. Neoprene and PTFE are two other common plastics included on one or both of the aforementioned lists.

All plastics can be destroyed by fire, and many give off toxic combustion products. Some burn very rapidly, but others are slow burning, self-extinguishing, or do not ignite at all, so careful selection of polymers and modifiers can be crucial in building applications. Flame-spread ratings, smoke-developed ratings, and toxicity of combustion products should be checked for each use of plastics within a building.

Plastics have much higher coefficients of thermal expansion and often require details that can accommodate large volume changes. Plastics tend not to be very stiff. They deflect considerably more under load than most conventional materials. Taken together with their combustibility, this severely limits their application as primary structural materials. Many also creep under prolonged loading, especially at elevated temperatures. In strength, plastics vary from fiber-reinforced composites that are as strong as many metals (but not as stiff) to cellular foams that can be crushed easily between two fingers.

Many unmodified plastics tend to degrade in the outdoor environment and are especially susceptible to attack by oxygen, ozone, and the ultraviolet component of sunlight. However, with adjustments in the chemistry of the material, these problems are overcome in plastics used for exterior applications such as glazing, roofing membranes, joint sealants, and coatings.

While thermoset plastics generally cannot be recycled, thermoplastic plastics are readily recyclable since they can be easily melted and reformed. Despite this, in the United States a lack of economic and infrastructure incentives results in less than 10 percent of plastic waste being recycled, with most of the remainder going to landfill. Significant amounts of recycled plastic do appear in some building products, for example, plastic wood, roof tiles, resilient flooring, insulation, and integrated concrete formwork.

Steel and Bronze

The chief advantage of steel (and to some extent bronze) as a frame material for windows is its strength, which permits steel sash sections to be slenderer than those of wood and aluminum (Figures 19.13 through 19.16). *Steel windows* may be made of steel coated in the factory with a long-lasting paint coating, galvanized steel, or stainless steel, depending on requirements for durability and appearance. Bronze windows are made in configurations similar to those for steel, usually with a natural patina finish. Steel and bronze are both less conductive of heat than aluminum, so windows made of these metals are less prone to forming condensation in cold weather. Where improved thermal performance is required, thermal break systems are also available.

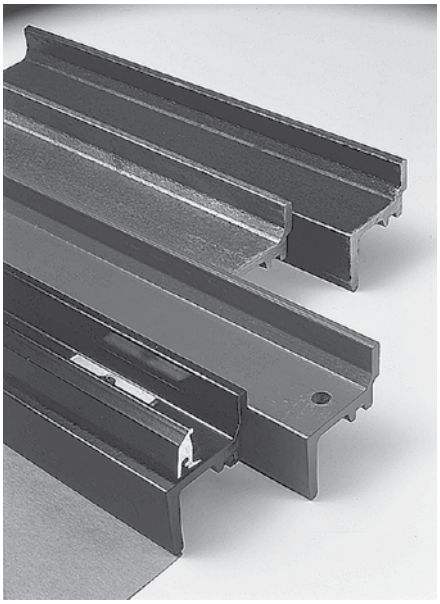


FIGURE 19.13
Samples of hot-rolled steel window frame sections, non-thermally broken. The nearest sample includes a snap-in aluminum bead for holding the glass in place. *(Steel windows by Hope's; Hope's photography by David Moog.)*

FIGURE 19.14
Cutaway sample of a non-thermally broken steel-framed window with aluminum glazing beads and factory finish. *(Steel windows by Hope's; Hope's photography by David Moog.)*

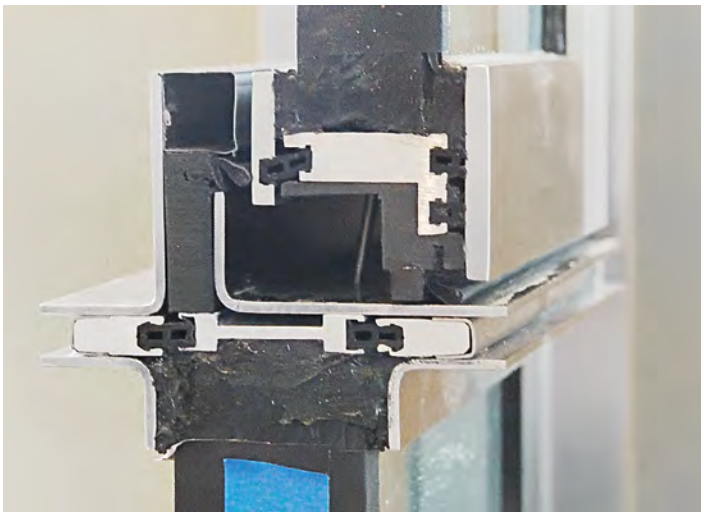


FIGURE 19.15
Section through a cold-rolled, thermally broken, stainless steel window frame. The exterior steel components (*left*) are separated by plastic thermal breaks and other low-density materials from steel parts on the interior (*right*). *(Photo by Joseph Iano.)*

FIGURE 19.16
Exterior detail view of the thermally broken stainless steel window frame seen in Figure 19.15. At bottom right is a fixed window unit, above that is an operable unit, and to the left is a door. *(Photo by Joseph Iano.)*

Muntins

In earlier times, large sheets of defect-free glass were difficult to produce, and window sashes were divided by thin wooden or metal bars called *muntins*, between which smaller glass lites were mounted. A typical double-hung window had its upper and lower sashes each divided into six lites and was referred to as a *six over six*. Muntin arrangements changed with changing architectural styles and improvements in glass manufacture. Today windows can be glazed with large, virtually flawless lites of glass. However, where the traditional look of muntined windows is desired, the effect is complicated by the necessity of using insulated glazing. One approach is to construct sashes with multiple, smaller sized double-glazed lites, held within true muntins deep enough to capture these thicker units. The result is a sash that is more expensive and less energy inefficient, with muntins that tend to appear thick and heavy. The least expensive option utilizes grids of imitation wood or plastic muntin bars clipped into each sash against the interior surface of the glass. (The bars are designed to be removed easily for glass cleaning.) Other options include imitation grids set within the insulating space of the glass units, or permanent or removable grids on both the outside and inside faces of the window.

Glazing

Single glazing is acceptable only in the mildest of climates, because of its low resistance to heat flow and the likelihood that moisture will condense on its interior surface in cool weather. Double glazing is the minimum that will meet energy code requirements in most climate zones. Where low-e coatings, dense gas fills, and thermally improved spacers were once considered exotic, high-performance options, these features are now increasingly common in many standard window units.

Figure 19.17 lists thermal transmittance properties for sample combinations of window frame material and glazing options. The listed U-Factors are overall values for complete window assemblies, accounting for differences in the thermal properties of the center of glass, edge of glass, sashes, and frames. When selecting actual windows, whole-unit U-Factors for any particular window are provided by the window manufacturer as determined by laboratory testing or computer simulation. In addition to thermal transmittance, solar heat gain coefficient (SHGC) and visible light transmittance (VT) are other important measures of a window system's performance. See Chapter 18 for a discussion of these properties.

FIGURE 19.17
Comparative approximate U-Factors for various window frame material and glazing combinations. Lower values correspond to better thermal performance. The values shown are averages. For any particular window, values vary with the product's materials and configuration. See Chapter 18 for a more in-depth discussion of glazing types.

	Overall U-Factor[a]		
Window Frame	**Single-Glazed**	**Double-Glazed, Low-e**	**Triple-Glazed, Low-e, Argon Fill**
Aluminum, no thermal break	1.2 *6.8*	0.60 *3.4*	
Aluminum, thermal break	1.1 *6.2*	0.50 *2.8*	0.30 *1.7*
Steel, no thermal break	1.2 *6.8*	0.45 *2.6*	0.40 *2.3*
Steel, thermal break	1.1 *6.2*	0.40 *2.3*	0.30 *1.7*
Wood, vinyl	0.95 *5.4*	0.30 *1.7*	0.20 *1.1*
GFRP	0.95 *5.4*	0.25 *1.4*	0.20 *1.1*
Aluminum clad wood, thermally improved			0.12 *0.70*

[a]U-Factor: Btu/ft^2-hr-^{o}F followed by *W/m^2-^{o}K*.

Installing Windows

Prior to installing a window, the wall *rough opening* is flashed with materials that protect against air and water leakage (Figure 19.18). *Self-adhered flashings* are made of adhesive-backed sheets of modified asphalt, synthetic rubber, reinforced plastic, or synthetic fibers. *Liquid-applied flashings* are troweled or rolled on and cured in place. On the face of the wall, the flashings overlap with the wall's air and water barrier material, creating a continuous air- and watertight boundary. Where exposed to view, *sheet metal flashings*, made from various corrosion-resistant metals, are used.

The wall rough opening is made slightly larger than the outside dimensions of the window itself. The narrow space remaining between the two, called the *shim space*, allows for precise positioning of the window. *Nail flange windows* are provided with a continuous metal or plastic flange around the perimeter of the window frame. The window is inserted into the rough opening, made level and square, and then secured to the wall with nails or screws driven through the flanges and into the rough opening framing. The flanges are set in sealant or protected with additional flashing material at the jambs and head to prevent water leakage. The flange at the sill is not sealed to the wall, so that water that penetrates into the space around the window can drain back to the exterior. Later, the flanges are concealed by exterior cladding or trim.

Non-flange windows are positioned within the rough opening with shims inserted into the shim space. Then, fasteners are driven through the frame and shims into the surrounding framing. In masonry walls, the fasteners may be driven into wood strips embedded within the masonry or screwed into metal clips laid into the masonry mortar joints.

To create a continuous, airtight boundary at the wall–window interface, a continuous sealant joint (*air seal*) is installed around all four sides of the window between the rough opening flashing and the back edge of the window frame. This seal also acts as a last line of defense against water leakage into the interior. To further protect the window opening from water running down the wall above, a sheet metal *head flashing* is installed just above the window. On the interior, the window opening is finished with trim components, such as the wood jamb extensions and casings shown in the accompanying figure.

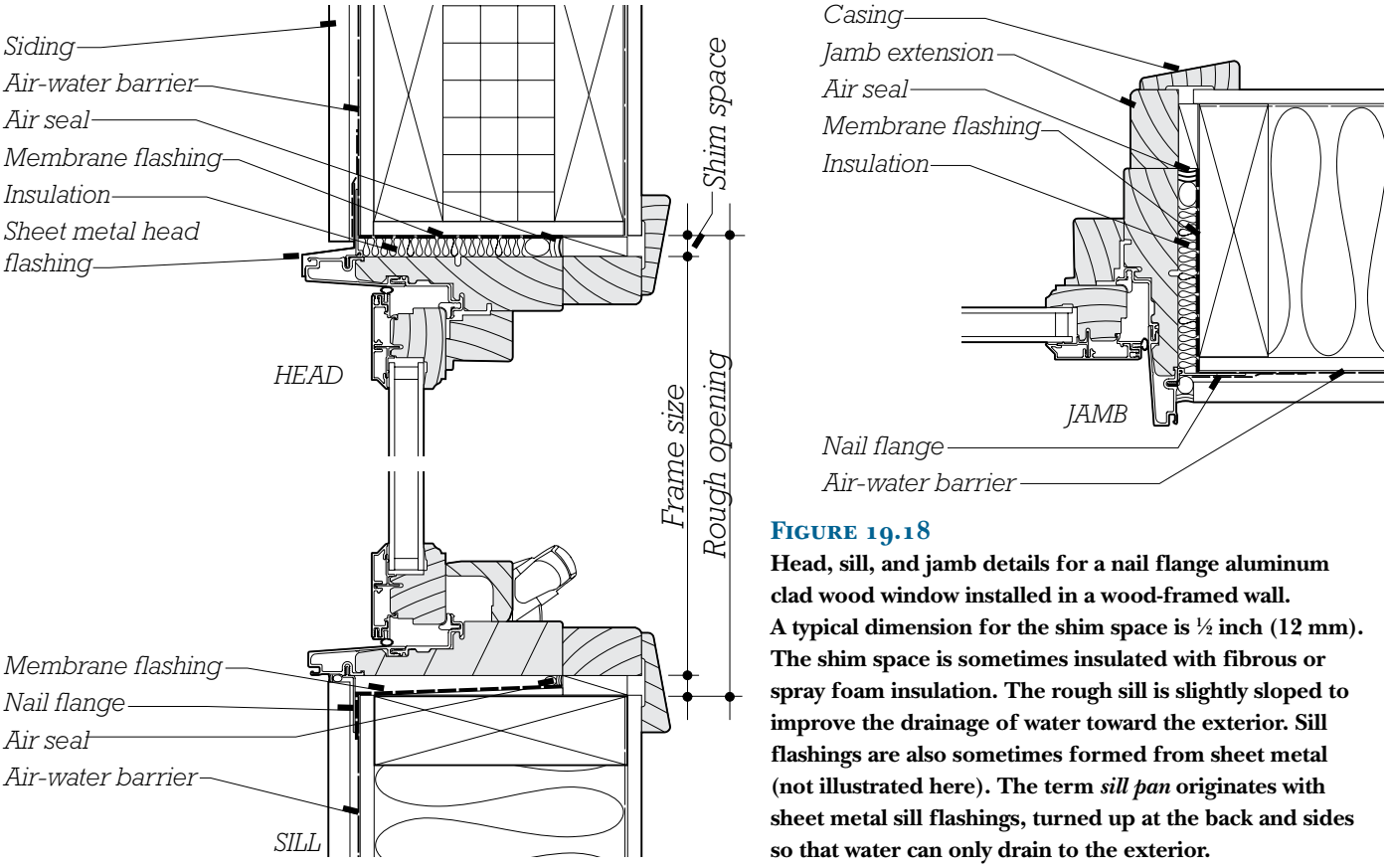


Figure 19.18

Head, sill, and jamb details for a nail flange aluminum clad wood window installed in a wood-framed wall. A typical dimension for the shim space is ½ inch (12 mm). The shim space is sometimes insulated with fibrous or spray foam insulation. The rough sill is slightly sloped to improve the drainage of water toward the exterior. Sill flashings are also sometimes formed from sheet metal (not illustrated here). The term *sill pan* originates with sheet metal sill flashings, turned up at the back and sides so that water can only drain to the exterior.

Sustainability and Windows and Doors

Energy Performance

Windows have a large impact on the thermal performance of the building enclosure. For example, consider a wall system with a thermal resistance of R-21 and windows with a thermal conductance of U-0.50. If windows make up 20 percent of the wall area, the overall performance of the wall and windows combined is reduced by two-thirds, to only R-7. Using an improved window with a thermal conductance of U-0.25 results in a combined thermal performance of R-11, a 50 percent improvement over the wall with less efficient windows.

Windows and doors create openings in the exterior wall that can leak substantial volumes of air, thereby adding to building energy losses. Careful detailing and installation is required to ensure the continuity of air barrier materials between windows and doors and the surrounding flashings and walls. Operable windows and doors should be securely gasketed or weatherstripped so as to minimize air leakage through these moving parts.

Windows can contribute to natural daylighting designs that improve productivity and lower energy consumption, and they can provide views to the outdoors that enhance building occupant well-being.

For more information about the sustainability of different materials used in the manufacture of windows and doors, see Chapter 3 (wood), Chapter 11 (steel), Chapter 18 (glass, plastics), this chapter's "Plastics in Building Construction" feature, and Chapter 22 (aluminum).

Building and Material Life-Cycle Impacts

- The metals industries, including metal door and window manufacturers, report the highest recycling rates of any demolished building components. For example, over 95 percent of aluminum building and construction scrap is recycled into new aluminum products.
- There is little recycling of scrap wood windows or doors.
- In the United States at this time, plastic windows and doors are generally not recycled.
- An aluminum window manufacturer EPD reports the following cradle-to-gate impacts per square meter (11 sq ft) of double-glazed window:

Nonrenewable primary energy consumption	63,000 MJ (60 million BTU)
Global warming potential	4800 kg (11,000 lb) CO_2 eq.
Fresh water consumption	50,000 L (13,000 gal)

- A wood door manufacturer EPD reports the following 100-year timeframe, cradle-to-grave impacts per 5-ply, structural composite lumber core, flush door, 7 feet × 3 feet × 1¾ inch (2.13 m × 0.91 m × 44.5 mm) in size:

Nonrenewable primary energy consumption	2300 MJ (2.2 million BTU)
Global warming potential	2.4 kg (5.4 lb) CO_2 eq.
Fresh water consumption	1400 L (370 gal)

Material and Production Attributes

- Many composite woods used in the manufacture of windows and doors contain wood waste products.

Unhealthful Materials and Emissions

- With a few exceptions, the materials used in window and door manufacture are generally low in toxic or harmful compound content. The health and environmental hazards associated with PVC, which is used in many plastic windows and doors, are discussed in more length earlier in this chapter's "Plastics in Building Construction" feature.
- Metals and glass do not emit unhealthful compounds. Composite wood products, as well as the finish coatings, sealants, and adhesives used in all types of window and door manufacture, should be low-emitting.

Responsible Industry Practices

- Metal window and door manufacturers report the highest rates of recycled material content in their products.
- Wood windows and doors may be manufactured from certified sustainable wood products.

Doors

Doors may be *exterior* or *interior*. Weather resistance is usually the most important functional factor in choosing exterior doors, whereas resistance to the passage of sound, or fire and smoke, are frequently important criteria in the selection of interior doors.

At the exterior, there are solid entrance doors, entrance and storefront doors that are mostly or entirely made of glass, storm doors, screen doors, vehicular doors for residential garages and industrial use, and revolving doors, to name just a few. Interior doors come in dozens of additional types. Many different modes of door operation are also possible, as shown in Figure 19.19. To simplify the

FIGURE 19.19
Some modes of door operation.

following discussion, we will focus on swinging doors for both residential and commercial use.

Wood Doors

At one time, nearly all doors were made of wood. In simple buildings, primitive doors made of vertical planks and Z-bracing were once common. In more finished buildings, *stile-and-rail doors* gave a more sophisticated appearance while also better managing moisture expansion and contraction of the wood. In this type of door, the infill panels are not glued to the styles and rails, but instead float in grooves that allow the panels to expand and contract without affecting the dimensions of the door overall. Stile and rail doors may be made of solid wood or composite materials with veneered faces and edges, and use many different wood species (Figure 19.20).

Today, genuine stile-and-rail wood doors continue to find use in high-quality interiors. But *flush doors*, consisting of flat, veneered wood faces assembled over a variety of core types, make up the largest share of the market. For exterior and higher-quality interior applications, these doors are constructed with *solid cores* made of wood composites, solid lumber strips, or fire-resistant mineral cores. For lighter-duty applications, lighter weight *hollow-core* doors with an interior grid made of paperboard honeycomb or spacers may be used.

There is a great variety of materials and construction techniques used in flush door construction, capable of producing doors meeting a wide range of cost, durability, and performance requirements. For example, a standard "commercial" quality solid-core door may be made of seven or nine layers in total (called 7-ply and 9-ply doors, respectively), assembled with water-resistant glue, and cured at air temperature in a press with up to 20 door assemblies in one stack. In comparison, a more expensive 5-ply architectural quality door may be assembled with a more sturdy core, thicker face veneers, and fully waterproof glue, and then individually pressed and cured under heat to form a more durable and higher finish quality product.

FIGURE 19.20
Some typical configurations for wood doors. The top row consists of flush doors. The middle row is made up of stile-and-rail doors.

Most flush wood doors are manufactured according to the Window and Door Manufacturers' ANSI/WDMA I.S.1A: Architectural Wood Flush Doors standard. This standard addresses door appearance and durability, and includes three performance grades—Standard Duty, Heavy Duty, and Extra Heavy Duty—intended for doors used in applications of increasingly heavy usage. High-quality wood doors, especially those custom-made in the woodworker's shop, may be fabricated according to the standards of the Architectural Woodwork Institute's *Architectural Woodwork Standards*, a comprehensive manual of materials and methods for custom woodwork.

Steel Flush Doors

Flush doors with faces of painted sheet steel, called *hollow metal doors*, are the most common type of door in nonresidential buildings (Figure 19.21). For economy, many interior steel doors have hollow cores. Solid-core doors are required for exterior use and in situations that demand increased fire resistance, more rugged construction, or better acoustical privacy between rooms.

Metal doors and most nonresidential wood doors are usually hinged to steel frames called *hollow metal frames*, which are also formed from sheet steel (Figure 19.22). *Knocked down (KD) steel frames* arrive on the construction site in three separate sections for the two jambs and head and are assembled in place into the previously prepared wall opening. *Welded steel frames* arrive on the construction site preassembled and welded at the corners. When used with gypsum-faced partitions, these frames must be erected before the wall because of the way in which the frame overlaps with the adjacent wall surfaces. Welded steel frames are stronger than KD frames and the absence of any visual seam at the frame corners is frequently considered more attractive. Hollow metal door frames installed in masonry walls are sometimes filled with gypsum or portland-cement grout, to improve sound deadening or to strengthen the frame and its anchors. However, care must be taken that excess moisture in the grout does not lead to corrosion of the frame or damage to wall finishes.

The sheet metal used in the manufacture of hollow metal doors and frames can be varied in thickness to achieve varying levels of durability. Where corrosion resistance is a concern, galvanized steel or stainless steel may be used in place of ordinary

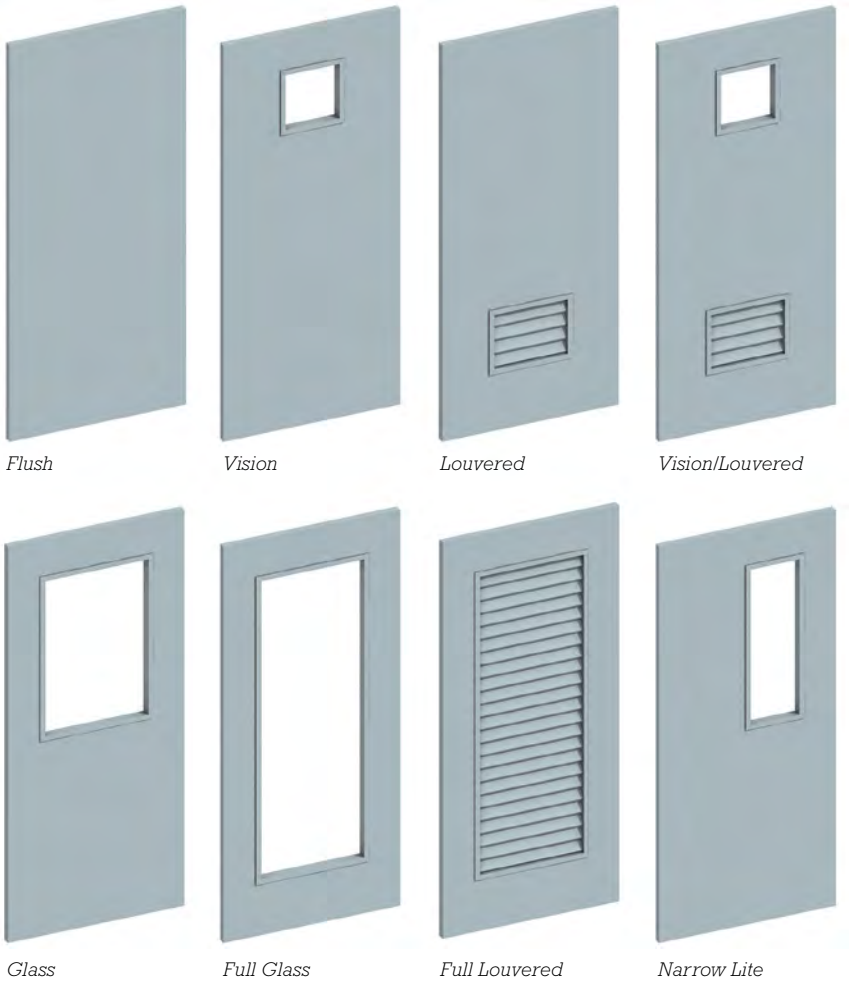
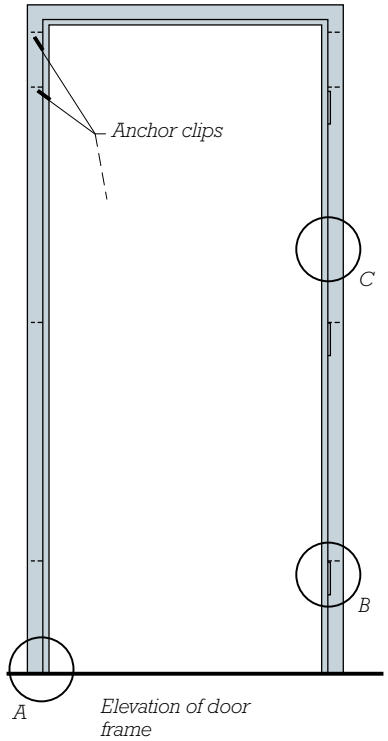
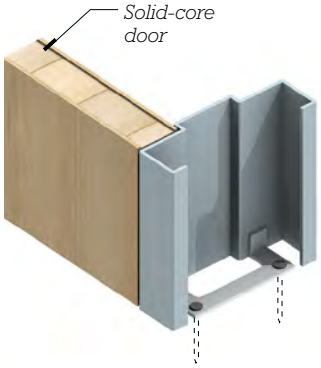
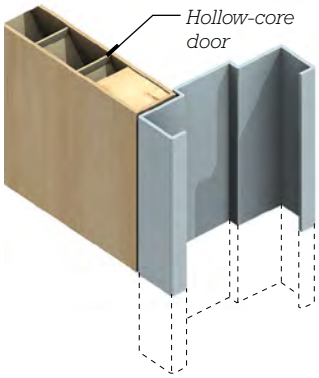


FIGURE 19.21
Some typical configurations for steel doors.





A. Jambs can be attached to the floor with powder-driven fasteners



A. Jambs can be attached to the floor by pouring floor topping concrete around the door frame

B. Reinforcement of jamb at hinge attachments

C. For jamb anchorage to masonry walls, loose sheet metal tees are inserted into the frame and built into mortar joints

C. For jamb anchorage to steel studs, sheet metal zees are factory-welded to the jambs to receive screws driven through the studs

C. For jamb anchorage to wire truss studs, notches key to the vertical members of the studs, and holes provide for tie wires

C. Jams are anchored to wood studs by nailing through holes in the jamb inserts

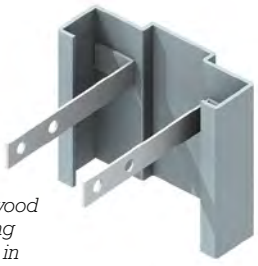


FIGURE 19.22
Details of hollow steel door frames. The lettered circles on the elevation at the upper left correspond to the details on the rest of the page.

steel. Or, as an alternative to steel frames, hollow metal doors can also be installed in frames of wood or aluminum.

Standard steel doors and frames are manufactured according to the Steel Door Institute's ANSI/SDI A250.8: Recommended Specifications for Standard Steel Doors and Frames. Custom, higher-quality hollow metal doors and frames may follow the Hollow Metal Manufacturers Association's ANSI/NAAMM-HMMA 861: Guide Specifications for Commercial Hollow Metal Doors and Frames.

Fiberglass Doors

Doors with *fiberglass reinforced plastic* (*FRP*) skins and subframes are manufactured as hollow-core doors with phenolic-coated paper or plastic honeycomb cores. Or they can be manufactured with solid, insulating plastic foam cores. FRP door faces can be flush or molded to resemble wood-grained stile-and-rail doors. Residential grade exterior FRP doors with insulating cores offer thermal performance superior to that of wood doors, and they do not suffer from the moisture expansion and contraction to which wood is prone. FRP doors can also be manufactured to meet a wide range of commercial and institutional requirements for heavier duty or fire-resistance-rated applications.

Fire Doors

Fire doors, that is, door openings within fire-resistance-rated walls, must themselves be fire rated. In such openings, both the door and frame are rated according to the period of time for which they are able to resist specified time and temperature conditions, as defined by NFPA 252: Standard Methods of Fire Tests of Door Assemblies, or by similar tests defined by Underwriters Laboratories. However, because door openings constitute only a limited area of most walls, and because combustible furnishings or materials are not normally located directly in front of doors, the required rating for such openings is often less than that required for the walls in which they are located. Figure 19.23 gives fire resistance ratings for door openings in rated walls as required by the International Building Code. For example, a door and frame in a 2-hour rated exit stairway enclosure must be at least 1½-hour rated, an opening in a 1-hour exit stairway enclosure must be 1-hour rated, and an opening in a 1-hour rated exit corridor, 20-minute (⅓-hour) rated. A standardized label is permanently affixed to the edge of each fire door and frame at the time of manufacture to designate its degree of fire resistance. These labels must not be painted over during construction, so that the fire rating of the door can be verified during future building inspections.

Most fire doors have solid mineral cores. For openings with ratings as high 1½ hours, both wood and metal doors and frames are available. For openings with higher

Type of Assembly	Assembly Rating (Hours)	Fire Door and Frame Rating
Fire walls and fire barriers	4	3
	3	3
	2	1½
	1½	1½
	1	¾
Vertical shaft, exit enclosure walls	2	1½
	1	1
Corridor fire partitions	1	20 minutes
	½	20 minutes
Other fire partitions	1	¾
	½	20 minutes
Exterior walls	3	1½
	2	1½
	1	¾
Smoke barriers	1	20 minutes

FIGURE 19.23

Required fire resistance ratings for doors, according to the International Building Code. In some applications, door openings are also rated for their ability to limit the passage of smoke or the rise of temperature on the non-fire side of the door. *(Part of Table 716.5, excerpted from the* 2012 International Building Code*, Copyright 2011. Washington, DC: International Code Council. Reproduced with permission. All rights reserved.* ***www.ICCSAFE.org****.)*

ratings, metal doors and frames must be used.

Glass used in fire doors must itself also be fire rated so that it will not break and fall out of the opening for a specified length of time when exposed to the heat of fire (see Chapter 18 for more information about fire-rated glass). The maximum size of glass may also be restricted, depending on the fire classification of the door and the type of rated assembly into which it is installed. Like glass in any door, glass in fire doors must also meet the requirements of safety glazing so that if broken, it does not create dangerous shards.

Egress Doors and Accessible Doors

Many doorways act as components of a building's egress system, or the path that occupants take when exiting a building during a fire or other emergency. Building codes require that such doorways be sufficiently wide to allow occupants to exit in a timely manner, with the width of any particular door dependent on the number of occupants served. For ease of operation, most egress doors must be side-hinged; they must not be too large; and when equipped with closers, they must not require too much force to swing open. The International Building Code requires egress doors serving 50 or more building occupants, as well as doors serving spaces classified as Hazardous Occupancy, to swing in the direction of egress travel so that they do not become impediments to occupants attempting to exit quickly. Even when locked, egress doors must remain readily openable from the side from which occupants may approach the door when exiting. To ensure the simplest possible operation under emergency conditions, some egress doors are required to be fitted with *panic hardware*, horizontal bars installed across the face of the door that unlock and unlatch the door whenever the bar is depressed.

Doorways along building routes designed to be accessible to persons with disabilities must meet requirements for minimum width, ease of operation, maximum height of threshold, and adequate clearance for approaching and opening the door.

There are many types of special-purpose doors, for example, X-ray shielding doors, which contain a layer of lead foil; electric field shielding doors, with an internal layer of metal mesh that is electrically grounded through the hinges; heavily insulated cold storage doors; and bank vault doors.

Door Hardware

Unlike windows, in which operating hardware is selected by the manufacturer and installed in the factory, most door hardware is selected by the designer independently from the door itself and installed on the construction site. Every door requires at least some hardware to control its motion and the means by which occupants manipulate it. Swinging doors are usually hung with two, three, or four *butt hinges*, depending on the door's weight. Each hinge consists of two leafs, one attached to the edge of the door and the other to the frame, and is joined by a pin around which the leafs rotate. For door operation, either a round door *knob* or flatter *lever* is provided, located a little below midheight of the door and close to the swinging edge of the door. Knobs are frequently used in residential occupancies, but wherever accessibility is a concern, levers that are more universally operable must be used. The knob or lever controls a *latch* in the door edge, disengaging it from the mating *strike* in the door frame and allowing the door to be swung open.

Depending on the functional requirements of the door, a bewildering array of additional hardware choices may be made, including, for example, locking and keying mechanisms to secure a door when closed, closing and opening devices to automate or provide assistance in door operation, stops mounted to walls or floors to limit door swing, silencers (small cushions) attached to the door frame that reduce door closing noise, viewers to see through a door, knockers, thresholds to manage transitions between materials on either side of the door, weatherstripping to control the flow of air and water around the door edges, soundstripping to control the passage of sound, kick plates to protect the door from damage, electronic interfaces with building communications and controls, and more. All of these come in various styles and operational configurations. Hardware can also be specified to differing levels of durability and with many different finishes. On larger projects, hardware specification is frequently performed by a consultant with specialized knowledge in these areas.

Doors may arrive on the construction as slabs or prehung. *Slab doors* are the doors themselves without any hardware or accessories attached. The installation of the door in its frame and the fitting of hardware are completed by skilled tradespersons on the construction site. *Prehung doors* arrive on the construction site with the doors installed in their frames, often with most or all additional hardware and accessories already in place. The installation of prehung doors requires less skilled labor and can proceed more quickly on site than the installation of slab doors.

Installing Doors

The installation of doors and frames in wall rough openings proceeds much like that described earlier in this chapter for windows, with the major exception that, in the case of interior doors, no flashings or other weather sealing related components are needed.

Other Window and Door Requirements

Safety Considerations in Windows and Doors

To prevent accidental breakage and injuries, glass within and adjacent to doors, and large lites within windows, must be made of safety glazing material. Tempered glass, laminated glass, and plastic glazing sheets can all meet the necessary requirements. See Chapter 18 for more information about safety glazing.

In many residential occupancies, buildings codes require at least one *emergency escape and rescue opening* in each bedroom, consisting of either a door to the exterior or a window that can be opened to an aperture large enough to permit occupants of the bedroom to escape through it and firefighters to enter through it.

Where operable windows in residential occupancies are more than 6 feet (1829 mm) above the exterior finished grade, the International Building Code requires that they be designed to minimize the risk of a child accidentally falling through them. Such windows must have sills not less than 36 inches (610 mm) above the interior finish floor. Or, where glazing is closer to the floor, the window unit must fixed, it must have openings sufficiently limited in size that a 4-inch (102-mm)-diameter sphere cannot pass through, or it must be protected with guards or other fall prevention devices.

Structural Performance and Resistance to Wind and Rain

Many performance aspects of windows and exterior doors are defined in *North American Fenestration Standard/Specification for Windows, Doors, and Unit Skylights* (*NAFS*), officially designated as AAMA/WDMA/CSA 101/I.S.2/A440. This standard establishes minimum requirements for air leakage, water penetration, structural strength, operating force, and forced-entry resistance of aluminum, plastic, and wood-framed windows, doors, and unit skylights.

The NAFS uses a letter designation called *Performance Class* and a numeric designation called *Performance Grade* to indicate the minimum capabilities of fenestration products. Performance Classes, in order of increasing capability, are R, LC, CW, and AW. In previous editions of the standard, these letter designations were associated with the terms "residential," "light commercial," "commercial," and "architectural," respectively. Although these plain word descriptions have been removed from newer versions of the standard, knowledge of them is still helpful in recalling the intended ranking of the letter designations themselves. Each Performance Class sets minimum criteria for resistance to wind loads, resistance to water penetration, and maximum air leakage.

Numeric Performance Grades correspond to maximum design wind pressures, used to determine the window or door's ability to resist these pressures structurally, as well as the component's ability to resist water penetration. For example, Grade 30 indicates a unit suitable for design wind pressures up to 30 psf (1440 Pa) and able to resist water penetration with wind pressures up to 4.6 psf (220 Pa). Grades are specified starting at 15 psf (720 Pa) and increase in increments of 5 psf (240 Pa). Each Class has a minimum acceptable Grade, and higher than minimum Grades can be specified where needed.

An example of a manufacturer's complete tested product designation is Class R—PG30: Size tested: 760 × 1520 mm (~30 × 60 in)—C, where R is the Performance Class; 30 is the Performance Grade; the pairs of numbers indicate the maximum size of the tested unit that meets these criteria, expressed as width by height, first in millimeters and then, in parentheses, in inches; and finally, the type of window, C, a casement. In practice, the designer may choose a Performance Class based on the building type and general expectations for durability of the system. For example, a Class LC window may be specified for a low-rise multifamily building, a Class CW window for a hospital or school, and a Class AW window for a large institutional or high-rise building. The required Performance Grade is determined based on the design wind pressures acting on the building, information that is usually provided by the structural engineer.

Thermal Performance

The National Fenestration Rating Council (NFRC) defines a program of energy efficiency testing and labeling based on two standards: NFRC 100: Procedure for Determining Fenestration Product U-Factors and NFRC 200: Procedure for Determining Fenestration Product Solar Heat Gain Coefficient and Visible Transmittance at Normal Incidence. The two most important properties included in these standards are thermal transmittance (U-Factor) and solar heat gain coefficient, both of which directly affect building energy consumption and are regulated by energy codes. Importantly, U-Factors represent the *overall thermal transmittance*, or *whole product heat loss*, of complete window, door, and skylight products. That is, they account for the combined contributions to thermal transmittance of the center of glass, edge of glass, framing, and other components. Visible light transmittance, air leakage, and condensation resistance ratings may also be included in NFRC ratings. An example of a standard label that is affixed to each NFRC-rated window is shown in Figure 19.24.

Windows sold in the Canadian market are also given an Energy Rating (ER), a relative indicator of heating season thermal performance. The ER combines U-Factor, air leakage, and solar heat gain measurements into a single number indicating

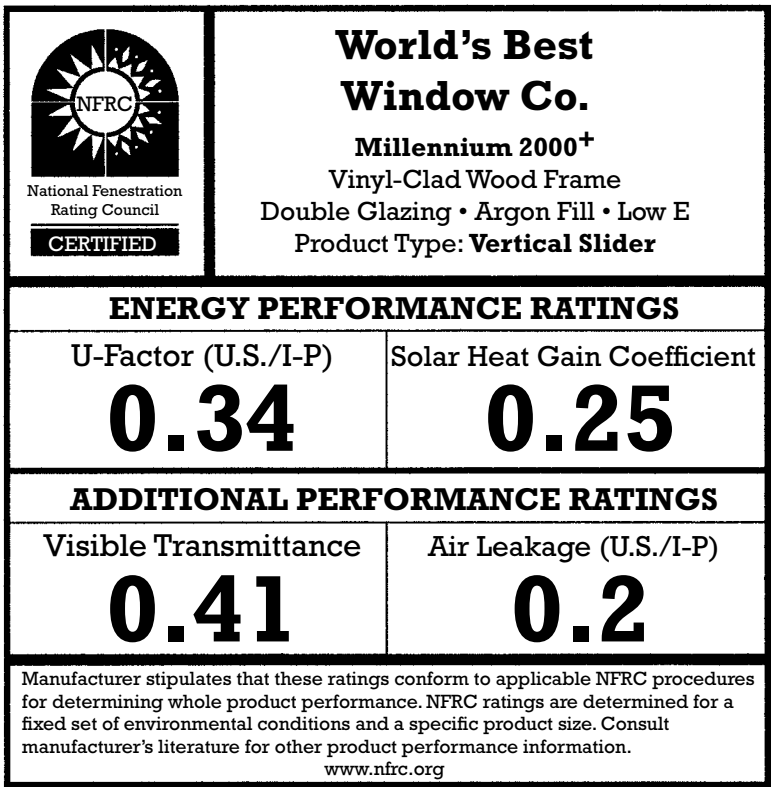


FIGURE 19.24
A sample NFRC certification label that is affixed to a window unit so that buyers may compare energy efficiencies.

net heat loss (negative ER) or heat gain (positive ER) over a defined set of conditions. ERs may be used to compare the relative thermal efficiency of windows, with a higher (or more positive) ER indicating better thermal performance than a window with a lower (or more negative) ER.

The AAMA/WDMA/CSA and NFRC standards are referenced by the International Building Code and National Building Code of Canada, making them the de facto standards for the selection of most North American building fenestration products.

Acoustic Isolation

Doors and windows can play an important role in limiting the transmission of sound into or out of classrooms, private offices, conference rooms, rehearsal rooms, recording studios, and other acoustically sensitive interior spaces, as well between the outdoors and indoors of a building.

Acoustic doors are made with core materials that are effective at reducing sound transmission through the door itself. Especially important are the acoustic seals, which must ensure a continuous seal around all four edges of the door when the door is closed. If these seals are not completely airtight, sound can easily bypass the door.

In *acoustic windows* (and glazed acoustic doors), glass is double- or triple-glazed, and made with thicker lites and fabricated with wider airspaces between the lites than in typical glass units, all measures that reduce sound transmission. Laminated glass may also be used. Especially when the two lites in the laminated unit differ in thickness, vibrations are dampened and sound transmission reduced.

Attention is also given to reducing sound transmission through the frames of acoustic doors and windows, as well as between the frames and the surrounding structure. Acoustic doors and windows are rated to the same sound transmission criteria used for wall assemblies, that is, Sound Transmission Class (see Chapters 16 and 22) and Outdoor-Indoor Transmission Class (see Chapter 16).

Impact Resistance

Buildings in hurricane-prone regions can be subject to powerful and destructive winds, and glazed openings in such buildings are especially vulnerable. The pressure of high-speed winds can cause glass to break, or it can suck whole lites out of their sashes, whole sashes out of their surrounding frames, or whole frames out of their rough openings. Glass can also be broken by rocks, severed tree limbs, and other debris launched by the wind with missile-like force. Once openings in a building are breached, the force of the wind can, in extreme cases, literally blow the roof off a structure. Even where a building structure remains intact, failed openings can admit large amounts of rainwater that can damage the building and its contents.

In the International Building Code, glazed openings in *wind-borne debris regions* must meet standards

for resistance to high-wind forces and debris impact. These regions include portions of the U.S. coasts along the Atlantic Ocean and Gulf of Mexico, the islands of Hawaii, and certain other U.S. territorial islands that are frequently subjected to hurricane-force winds. In these regions, most glazed openings must meet the requirements of two tests, ASTM E1996 and E1886, which subject assemblies to airborne "missiles" and cyclical air pressures to determine their ability to remain in place under hurricane-like conditions. The testing can be dramatic: For windows destined for installed locations not more than 30 feet (9.1 m) above grade, a 9-pound, roughly 8-foot-long (4.1 kg, roughly 2.4-m-long) 2 × 4 is fired endwise toward the window from a special cannon at a speed of 34 mph (55 kph). Although the glass is permitted to crack, it must survive in place, without being penetrated by the wood member.

Such *impact-resistant openings* (also sometimes referred to as *hurricane-rated openings*) are fitted with laminated glass with a heavy interlayer of PVB (polyvinyl butyral) or other similarly tough, viscous plastic. They also have stronger glazing (gasketing) systems to better hold the glass units in place, their frames are structurally reinforced, and they are fastened into their rough openings with suitably strong attachment hardware. As an alternative to providing impact-resistant openings in one- and two-story buildings, the code permits the use of precut plywood or

FIGURE 19.25
The narrow sight lines of steel windows and doors are evident in this photograph. *(Steel windows by Hope's; Hope's photography by David Moog.)*

FIGURE 19.26
Custom Alaskan yellow cedar wood doors on architect Steven Holl's Chapel of St. Ignatius. *(Photo by Joseph Iano.)*

OSB panels that can be fastened into place over the outside of such openings when needed to act as temporary storm shutters.

Blast Resistance

In buildings subject to heightened security requirements, windows, curtain walls, and other glazing may be designed for resistance to the force of explosive blasts. In the United States, two federal standards for designing *blast-resistant glazing systems* are used, one published by the Department of Homeland Security's Interagency Security Committee and the other by the Department of Defense.

Design for blast resistance involves defining the force of the blast and its distance from the glazing system, as well as the glazing system's response to the blast. Of particular concern is the extent to which glass remains intact within the assembly or to which it shatters and disperses as hazardous fragments that could injure building occupants. Like impact-resistant glazing, blast-resistant glazing typically relies on laminated glass and reinforced framing and attachment systems.

MasterFormat Sections for Windows and Doors

08 11 00	**METAL DOORS AND FRAMES**
08 11 13	Hollow Metal Doors and Frames
08 14 00	**WOOD DOORS**
08 14 16	Flush Wood Doors
08 14 33	Stile and Rail Wood Doors
08 15 00	**PLASTIC DOORS**
08 16 00	**COMPOSITE DOORS**
08 16 13	Fiberglass Doors
08 51 00	**METAL WINDOWS**
08 51 13	Aluminum Windows
08 51 16	Bronze Windows
08 51 19	Stainless-Steel Windows
08 51 23	Steel Windows
08 52 00	**WOOD WINDOWS**
08 52 13	Metal-Clad Wood Windows
08 52 16	Plastic-Clad Wood Windows
08 53 00	**PLASTIC WINDOWS**
08 53 13	Vinyl Windows
08 54 00	**COMPOSITE WINDOWS**
08 54 13	Fiberglass Windows
08 61 00	**ROOF WINDOWS**
08 62 00	**UNIT SKYLIGHTS**
08 71 00	**DOOR HARDWARE**

Key Terms

window
fixed window
single-hung window
double-hung window
sash
sliding window
projected window
casement window
awning window
hopper window
inswinging window
pivot window
jamb
head jamb, head
side jamb
sill
stool
interior casing
exterior casing
apron
triple-hung window
tilt/turn window
pivoting window
top-hinged inswinging window
skylight
venting skylight
roof window
French door
sliding door
terrace door
wood window
clad wood window
thermal break
aluminum window
plastic window
glass-fiber-reinforced plastic (GFRP) window, fiberglass window
pultrusion
plastic
synthetic rubber, elastomer
polymer
monomer
copolymer
thermoplastic
thermosetting
crosslinked
plasticizer
stabilizer
filler
extender
reinforcing fibers
flame retardant
(plastic) composite
(plastic) laminate
extrusion
molding
calendaring
blow forming
vacuum forming
steel window
muntin
six over six
rough opening
self-adhered flashing
liquid-applied flashing
sheet metal flashing
sill pan
shim space
nail flange window
non-flange window
air seal
head flashing
door
exterior door
interior door
stile-and-rail door
flush door
solid-core door
hollow-core door
hollow metal door
hollow metal frame
knocked down steel frame, KD steel frame
welded steel frame
fiberglass reinforced plastic (FRP) door
fire door
panic hardware
butt hinge
door knob
door lever
latch
strike
slab door
prehung door
emergency escape and rescue opening
Performance Class
Performance Grade
overall thermal transmittance, whole product heat loss
acoustic door
acoustic window
wind-borne debris region
impact-resistant opening, hurricane-rated opening
blast-resistant glazing system

Review Questions

1. List in detail the primary functional requirements for windows in each of the following situations:

   a. A residential bathroom in an urban apartment building

   b. A display window in a department store

   c. A teller's window in a drive-in banking facility

   d. A bedroom in Nome, Alaska

   e. A living room in Hilo, Hawaii

2. Select a type of window operation for each of the following situations:

   a. A window that can be left open in the rain

   b. A window that must induce the maximum possible ventilation from passing breezes

   c. A window in a high-rise office building

   d. A window to frame an expansive view of distant mountains

   e. A window that can be operated as either a casement or a hopper

3. Compare the advantages and disadvantages of wood, plastic-clad wood, PVC, aluminum, and steel as window frame materials.

4. A well-insulated residential wall has an R-value of 20 and U-Factor of 0.05 (in U.S. units). Compare the heat loss per square foot of the worst- and best-performing window and glazing combinations listed in Figure 19.17 with that of this wall.

5. Select a type of door for each of the following situations:

   a. Your bedroom closet

   b. A front door of a house

   c. A front door of a department store

   d. A door between the industrial arts shops and the cafeteria in a high school

   e. A door on a warehouse loading dock

Exercises

1. Obtain a copy of the building code that applies to the area in which you currently live. What fire resistance ratings are required for doors in the following situations?

   a. A door between a hotel room and a public corridor

   b. A door in an egress stair enclosure

   c. A door in a fire wall between an iron foundry and an office building

   d. A door between a single-family residence and its attached garage

2. Obtain catalogs from several window manufacturers. From them, select a set of windows for a one-room wilderness cabin of your own design.

3. Examine closely the windows in the room in which you are now sitting. What type of glazing do they have? What type of frame? How do they operate? How are they weatherstripped? Do these windows make sense to you in terms of today's energy efficiency requirements and your own feelings about the room? How would you change them?

Selected References

Carmody, John et al. *Residential Windows: A Guide to New Technologies and Energy Performance* (3rd ed.). New York, W. W. Norton, 2007.

This book is a clearly written, well-illustrated introduction to considerations of energy efficiency in residential windows.

Hollow Metal Manufacturers Association. Various technical documents, including "Recommended Selection and Usage Guide for Hollow Metal Doors and Frames" and "Hollow Metal Doors, Hollow Metal Frames, and Fire Rated Hollow Metal Doors & Frames." Chicago, National Association of Architectural Metal Manufacturers, various dates.

These two guides, and others available from the NAAMM, are useful to the designer and specifier of steel doors and frames.

Selkowitz, Stephen et al. *Window Systems for High-Performance Buildings*. New York, W. W. Norton, 2003.

This book addresses the myriad performance requirements and selection criteria for commercial glazing and window systems.

Window and Door Manufacturers Association. Various technical documents, including "ANSI/WDMA I.S.1A: Interior Architectural Wood Flush Doors" and "AAMA/WDMA/CSA 101/I.S.2/A440: North American Fenestration Standard." Des Plaines, IL, various dates.

These two standards and other technical guides available from the WDMA are useful to the designer and specifier of doors and windows.

Websites

American Architectural Manufacturers Association: www.aamanet.org

Andersen Windows & Doors: www.andersenwindows.com

Ceco Door (steel doors): www.cecodoor.com

Efficient Windows Collaborative: www.efficientwindows.org

Efficient Windows Collaborative, Windows for High-Performance Buildings: www.commercialwindows.org

Hollow Metal Manufacturers Association: www.naamm.org/hmma

Hope's (steel windows and doors): www.hopeswindows.com

Marvin Windows and Doors: www.marvin.com

National Fenestration Rating Council: www.nfrc.org

Steel Door Institute: www.steeldoor.org

Steel Window Institute: www.steelwindows.com

Whole Building Design Guide, Windows: www.wbdg.org/guides-specifications/building-envelope-design-guide/fenestration–systems/windows

Window & Door Manufacturers Association: www.wdma.com

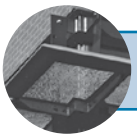
Windows and Daylighting (Lawrence Berkeley National Laboratory): windows.lbl.gov

Zola European Windows: www.zolawindows.com

20

Cladding with Masonry and Concrete

- **Masonry Veneer Curtain Walls**
  - Prefabricated Brick Panel Curtain Walls
- **Stone Curtain Walls**
  - Stone Panels Mounted on a Steel Subframe
  - Monolithic Stone Cladding Panels
  - Stone Cladding on Steel Trusses
  - Posttensioned Limestone Spandrel Panels
  - Thin Stone Facings
- **Precast Concrete Curtain Walls**
  - Glass-Fiber-Reinforced Concrete Curtain Walls
- **Exterior Insulation and Finish Systems**



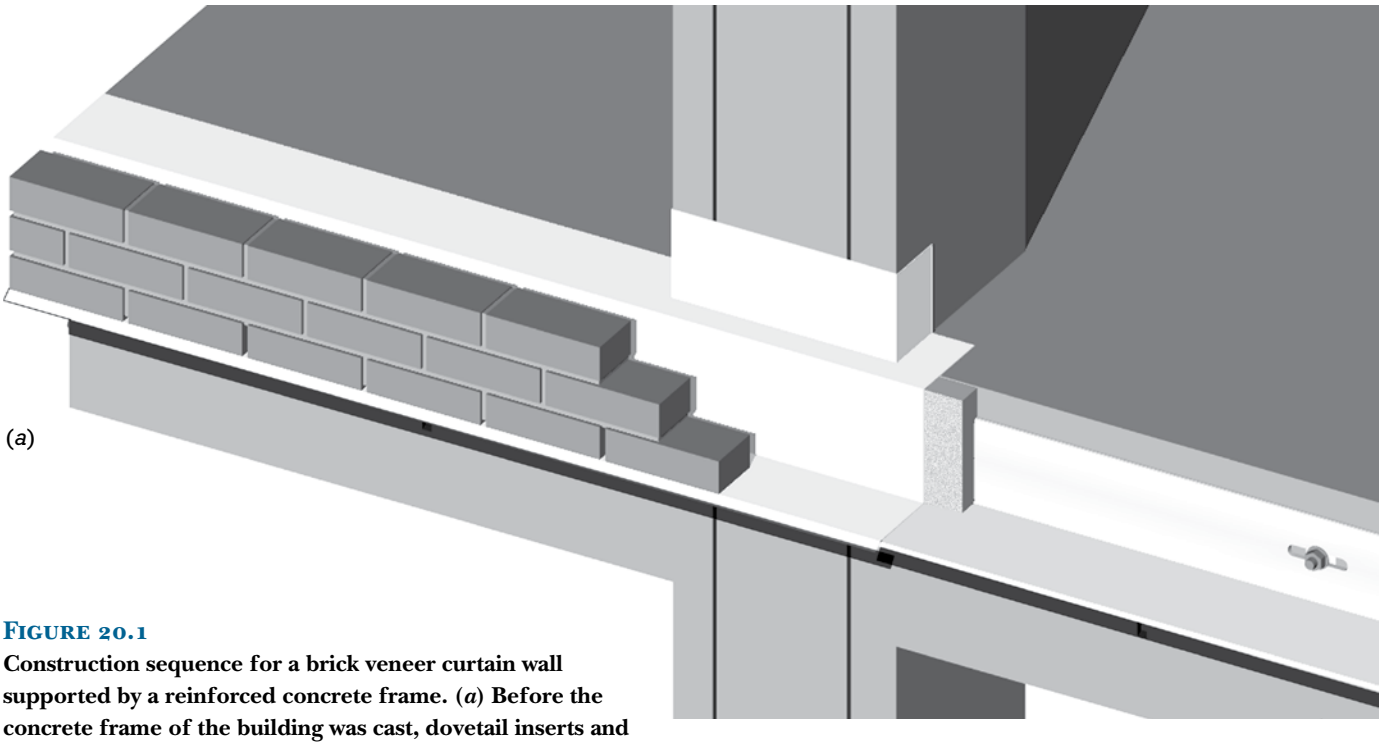
Case Study: Seattle University School of Law

Precast concrete cladding expresses solidity and room-size scale in this Embassy Suites hotel by Freiheit Architecture. *(Photo by Joseph Iano.)*

Buildings framed with structural steel or concrete are often clad with brick, stone, or precast concrete. These substantial materials, though suspended from the loadbearing frame of the building, still impart a sense of mass, solidity, and permanence. These thin, facings, however, do not behave the same way as the traditional solid loadbearing walls they sometimes mimic. When mounted on a frame, these brittle claddings must adjust to the movements of the frame and maintain weathertightness despite being applied in a layer only a few inches thick. Careful detailing and good construction practices are required to make this possible.

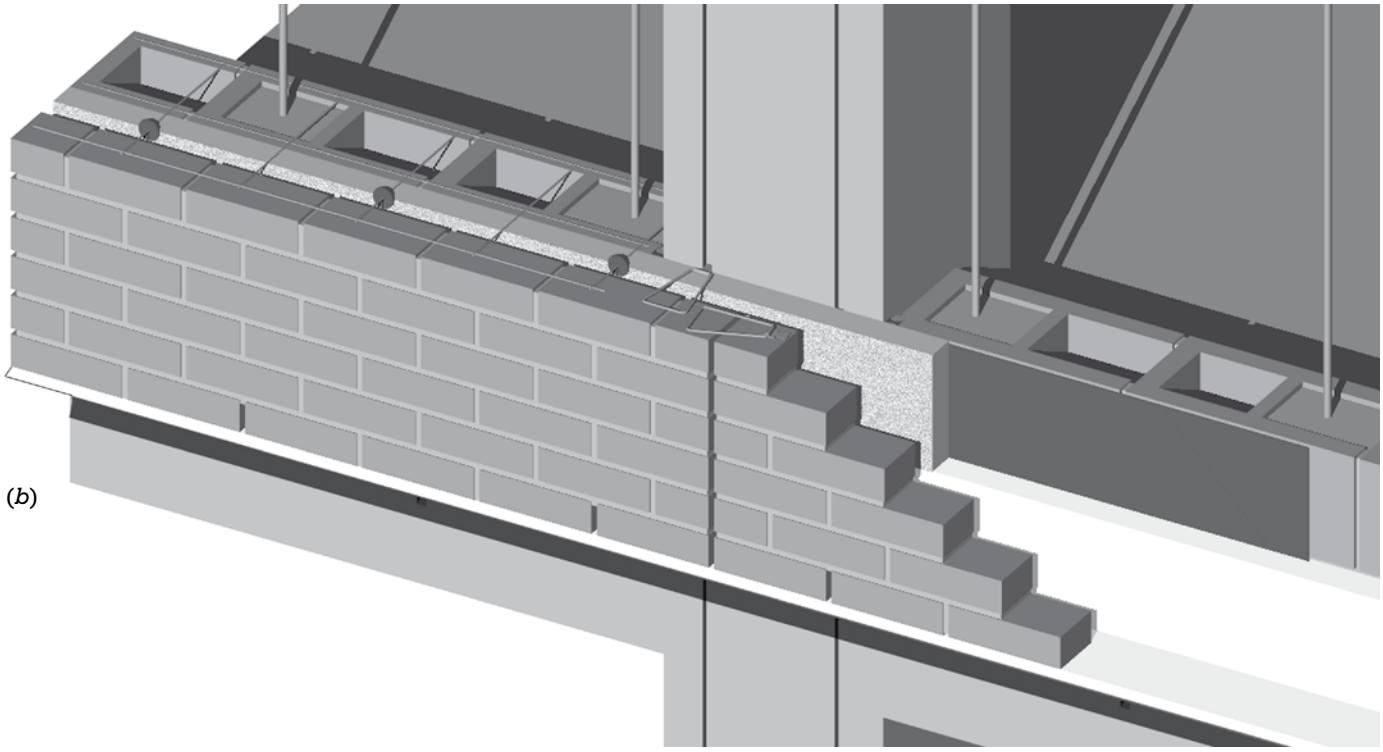
Masonry Veneer Curtain Walls

Figure 20.1 illustrates steps in the construction of brick *masonry veneer* cladding, consisting of a single wythe of brick masonry separated by a *cavity* from a *backup wall* and applied to a reinforced concrete frame. The veneer may also be made of stone. The veneer is erected brick by brick or stone by stone with conventional

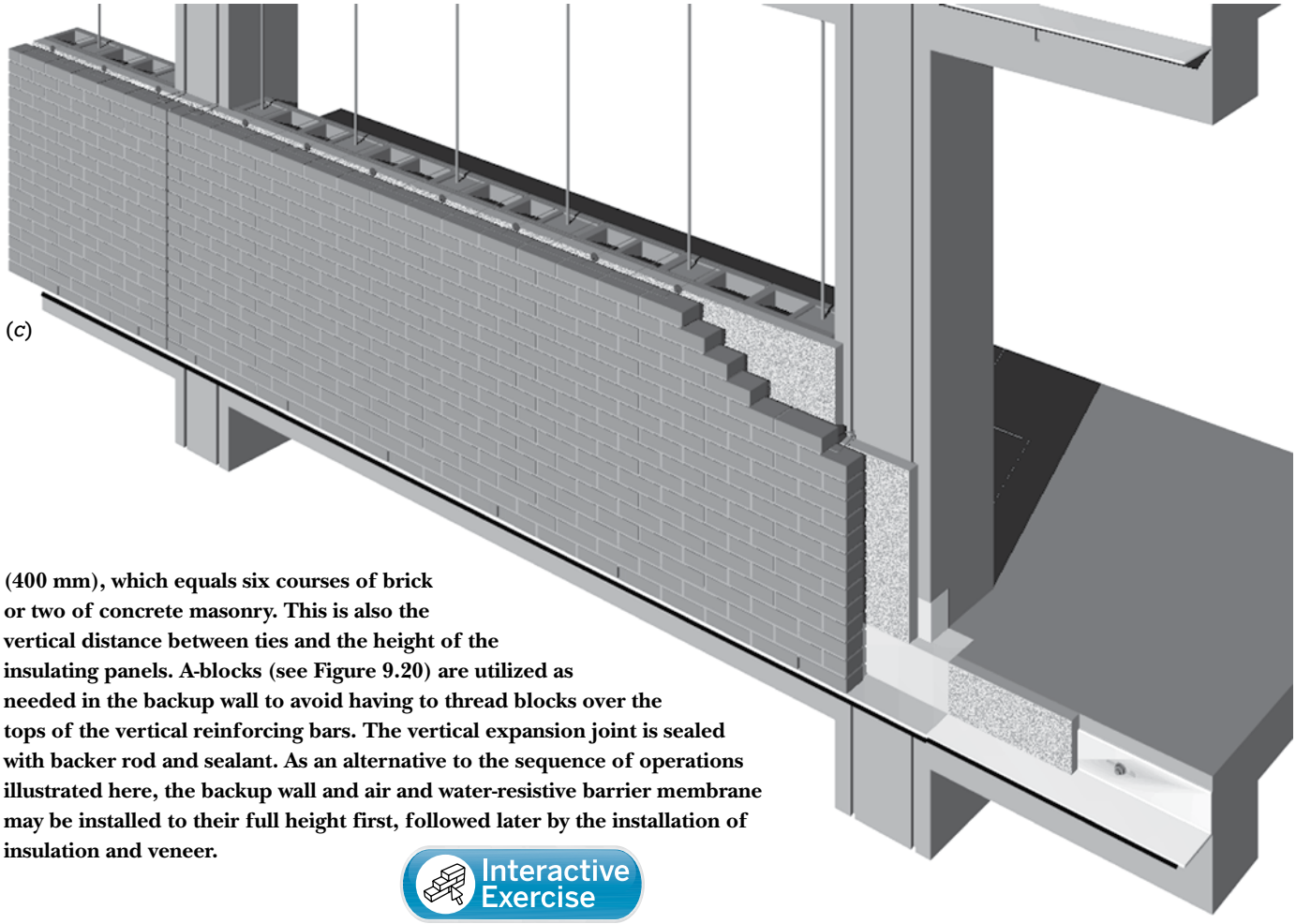


(*a*)

Figure 20.1
Construction sequence for a brick veneer curtain wall supported by a reinforced concrete frame. (*a*) Before the concrete frame of the building was cast, dovetail inserts and steel embed plates were put into the formwork that later will become part of the attachments for the shelf angle and brick veneer (see the Chapter 15 sidebar "Fastening to Concrete" for pictures of inserts such as these). To begin installation of the veneer, a steel shelf angle is attached to the spandrel beam. (See Figure 20.2 for more information about shelf angle attachments.) A slab of polystyrene foam or mineral wool board thermal insulation (gray) is placed over the upright leg of the shelf angle, and a continuous flashing (white) is installed over the shelf angle, the insulation, and the edge of the floor slab. This flashing also wraps around the front of the column. Seams in the flashing are overlapped and made watertight with sealant. The first course of brickwork is laid directly on the shelf angle and flashing, without a bed joint of mortar. Every third head joint is left open in this first course to form weep holes. Three courses of brickwork bring the veneer up to the level of the floor slab. (*b*) The first course of the concrete masonry backup wall is laid. Vertical reinforcing bars are grouted into the hollow cores of the backup wall at intervals specified by the structural engineer. An air and water-resistive barrier membrane, traditionally an asphaltic mastic and more recently a liquid-applied elastomeric coating, is applied to the face of the backup wall. Three more courses of brick veneer bring the top of the veneer up to the level of the top of the first course of concrete masonry. Additional insulation is placed against the concrete masonry. A combination joint reinforcing and masonry tie made of heavy stainless steel wires is laid on top of the masonry, tying the brick veneer to the backup wall. Plastic clips are snapped onto the rods of the joint reinforcing to hold the insulation in position. A vertical expansion joint in the brick veneer is provided at the centerline of each column. A heavy wire masonry tie in a dovetail slot anchors the brick veneer to the column on each side of the joint; in this view, another such anchor is lying loose on top of the bricks ready to be installed. (*c*) The wall rises in vertical increments of 16 inches



(*b*)



(*c*)

(400 mm), which equals six courses of brick or two of concrete masonry. This is also the vertical distance between ties and the height of the insulating panels. A-blocks (see Figure 9.20) are utilized as needed in the backup wall to avoid having to thread blocks over the tops of the vertical reinforcing bars. The vertical expansion joint is sealed with backer rod and sealant. As an alternative to the sequence of operations illustrated here, the backup wall and air and water-resistive barrier membrane may be installed to their full height first, followed later by the installation of insulation and veneer.

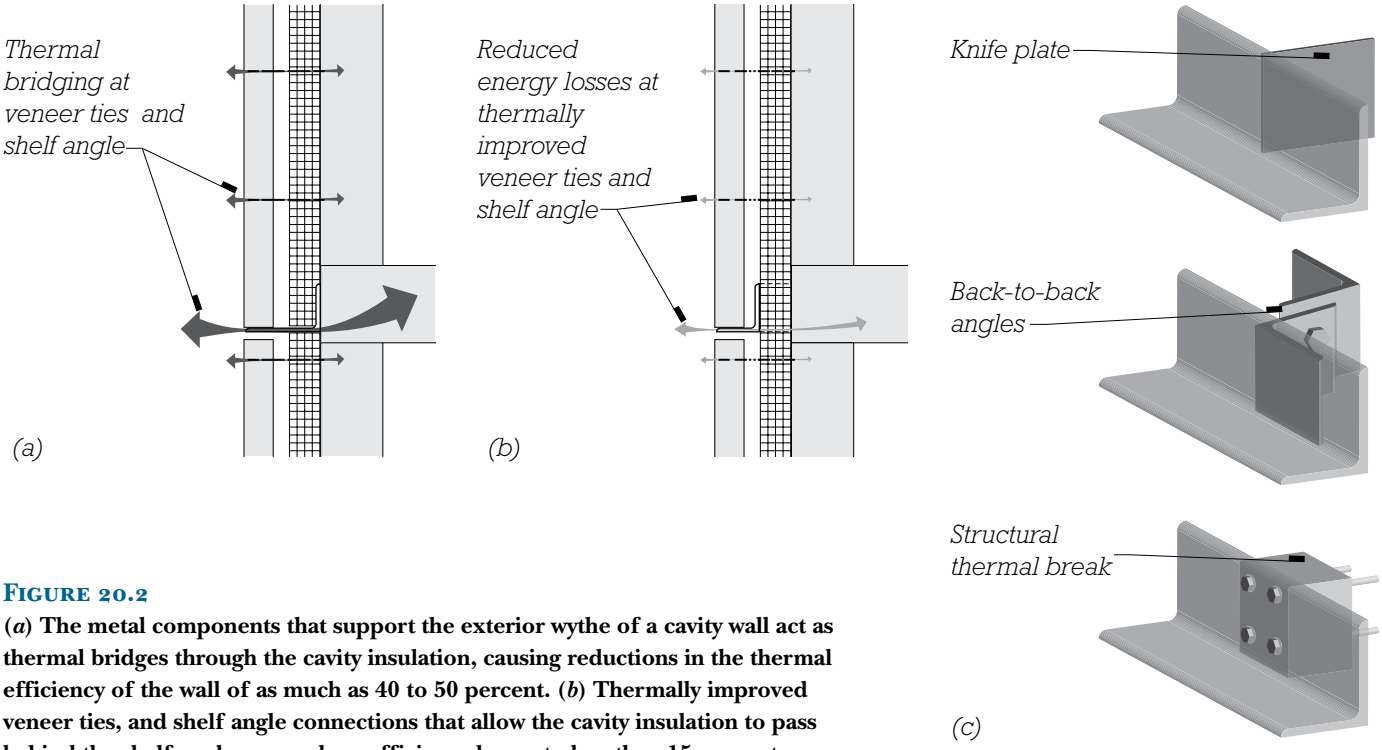


FIGURE 20.2

(*a*) The metal components that support the exterior wythe of a cavity wall act as thermal bridges through the cavity insulation, causing reductions in the thermal efficiency of the wall of as much as 40 to 50 percent. (*b*) Thermally improved veneer ties, and shelf angle connections that allow the cavity insulation to pass behind the shelf angle, can reduce efficiency losses to less than 15 percent. (*c*) Three improved shelf angle connections. The *knife plate* is a welded connection. Overlapping or back-to-back angles can be bolted. *Structural thermal breaks* incorporate high-strength, low thermal conductivity composites into bolted connections. Using stainless steel in connections such as these can further improve thermal efficiency because this metal is roughly three times less conductive of heat than ordinary steel. Improved veneer ties (not shown) incorporate high-strength plastic components to act as thermal breaks.

mortar, starting from a steel *shelf angle* that is attached to the structural frame at each floor (Figure 20.2).

Many steps in the process and details of the assembly are essentially the same as for a masonry cavity wall of a single-story building, but there are some crucial differences in larger buildings: To prevent stress in the veneer caused by movements in the frame of the building or expansion and contraction in the masonry itself, the veneer is divided into rectangular panels of reasonable size surrounded by expansion joints that can absorb these movements. At each floor level, a *horizontal expansion joint* (*soft joint*) is provided beneath the shelf angle (Figure 20.3). This joint is made wide enough to absorb the sum of column creep, brick expansion, spandrel beam deflection, and tolerances for construction inaccuracies while not exceeding the movement capacity of the sealant. Similarly, *vertical expansion joints* protect the veneer from stresses caused by movements in the horizontal plane (Figure 20.4).

The flashing above the shelf angle plays an important role in capturing water that reaches the cavity and conducting it back out of the wall. It runs continuously along the shelf angle and should project beyond the face of the veneer sufficiently to form an effective drip. Terminating the flashing at the edge of, or slightly behind, the face of the veneer invites water to be drawn under the flashing by capillary action. This can lead to corrosion of the shelf angle, or, in cold climates, freeze-thaw damage to the veneer. Often, a combination of materials are used for such *through-wall flashings*. Stiff, corrosion-resistant sheet metals, such as copper or stainless steel, are used where the flashing projects from the wall or where the flashing is unsupported within the cavity. Flexible, waterproof membranes, such as self-adhering bituminous or EPDM sheets, are easier to form into shapes and seal reliably at edges and penetrations. They are frequently used in concealed parts of the wall. Brick veneer cladding with a drainage cavity and backup wall is an example of drained cladding, a type of exterior wall construction discussed in more detail in Chapter 16.

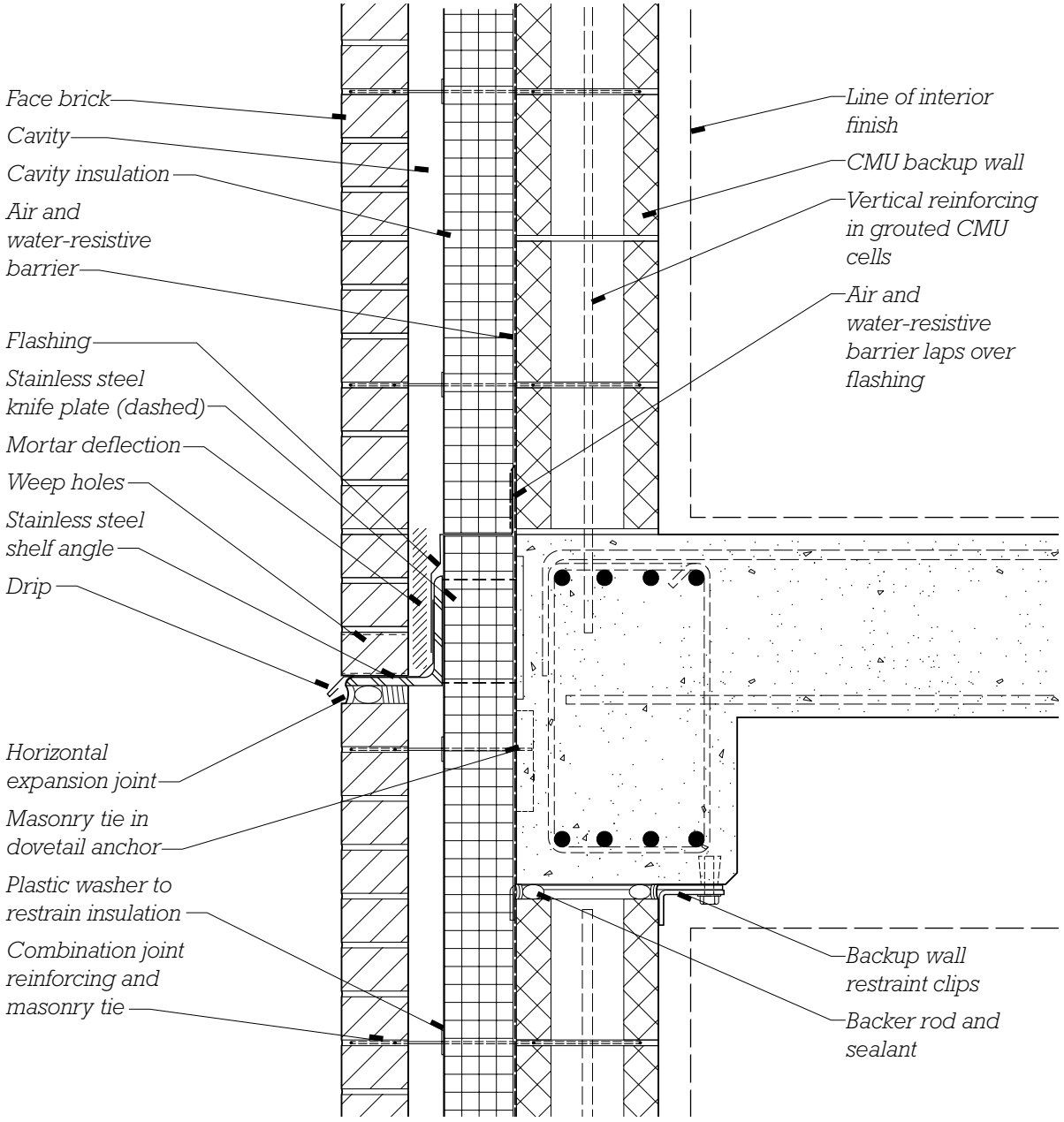


FIGURE 20.3

Section through a brick veneer curtain wall similar to that illustrated in Figure 20.1. The shelf angle is supported by regularly spaced knife plates (see Figure 20.2). Restraint clips, attached to the bottom of the concrete spandrel beam, brace the top of the CMU wall against wind loads while allowing the spandrel beam to deflect under load. The joint under the beam is kept free of mortar and sealed with backer rod and sealant to allow movement. Mortar deflection material protects the bottom of the cavity from becoming clogged with mortar droppings (see Figure 10.5).

(*a*) (*b*)

FIGURE 20.4

(*a*) A carefully detailed brick curtain wall by architect Kallman McKinnell & Wood covers the steel frame of Hauser Hall at Harvard University. Notice the vertical expansion joint near the far-right corner. (*b*) At the base of Hauser Hall, the facing wythe is made of limestone blocks. The backup wall consists of steel studs and gypsum sheathing panels. A vertical expansion joint is visible in the far-left corner in this view. *(Photos © Steve Rosenthal.)*

Stone and brick veneer cladding may also be constructed with a backup wall constructed of light gauge steel studs covered with water-resistant gypsum or cement board sheathing panels (Figures 20.5 and 20.6). In comparison to backup walls of concrete masonry, those made from metal framing are lighter in weight, faster to erect, more accommodating of electrical wiring, and readily covered with a great variety of interior finish materials. However, a steel stud framed wall is more flexible than one made of concrete masonry and prone to greater deflections under the pressures of the wind. If these deflections are too great, mortar joints begin to crack, the veneer is weakened, and water leakage into the cavity increases. In severe cases, this can lead to deterioration of the sheathing panels and corrosion of masonry ties and their connections to studs. For these reasons, the stud backup system is engineered conservatively, with sufficient stiffness to protect the veneer from wind load stresses, and the sheathing material, ties, and fasteners are selected for their resistance to moisture and corrosion.

Another consideration unique to metal stud backup walls is the attachment of the masonry ties. Except in walls that experience relatively low wind and seismic forces, the ties cannot bear against the sheathing panels or cavity insulation but must make direct contact with the metal studs. The ties shown in Figure 20.5 consist of metal plates that are screwed to the sides of the studs and pass through the sheathing, air and water-resistive barrier, and cavity insulation. Other ties are configured to be installed working exclusively from the exterior side of the backup wall, with, for example, pointed metal legs that are pushed through the insulation and sheathing to make contact with the faces of the studs. Wherever ties pierce the air and water-resistive barrier membrane, care must be taken to seal the penetrations to maintain the continuity of the membrane.

The structural frame of a building is never absolutely flat or plumb. Thus, the system for attaching shelf angles must allow adjustment, so that the veneer may be constructed

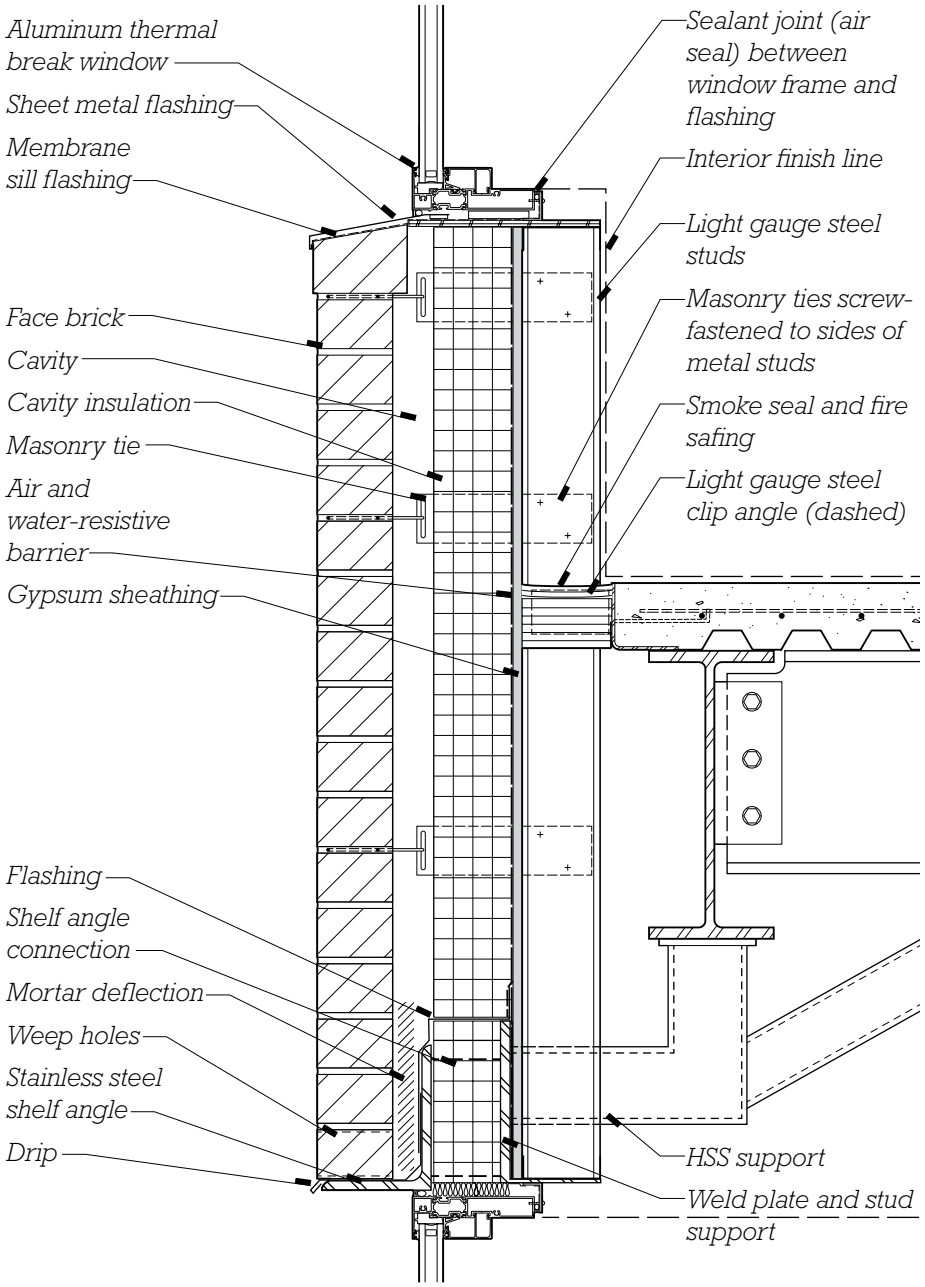


Figure 20.5
A section of a brick curtain wall with metal stud backup. The veneer is supported on a shelf angle connected to the supporting structure using methods such as those shown in Figure 20.2. The stud framing is supported at its bottom on a continuous steel plate and is braced laterally by sheet metal clip angles fastened between the studs and a plate at the edge of the concrete slab. Insulation is located exclusively within the cavity. This minimizes heat losses from thermal bridging through the metal framing. It also keeps the metal framing and masonry tie connections fully within the thermal enclosure of the building, where they are best protected from moisture and corrosion. The *smoke seal* and *fire safing* slow the passage of smoke and fire between floors in the event of a building fire. Depending on building size and other factors, fireproofing of the structure or exterior wall may also be required (not shown).

in a more precisely vertical plane with level courses. The back-to-back angle support shown in Figure 20.2 is one such example. Slotted holes in the two angles allow for precise positioning during installation. Later, the angles are welded to permanently fix their positions. Other adjustable support strategies for attachment of curtain wall components, such as angle bracing with slotted bolt holes, shimming, and adjustable leveling bolts, are illustrated in later figures in this chapter.

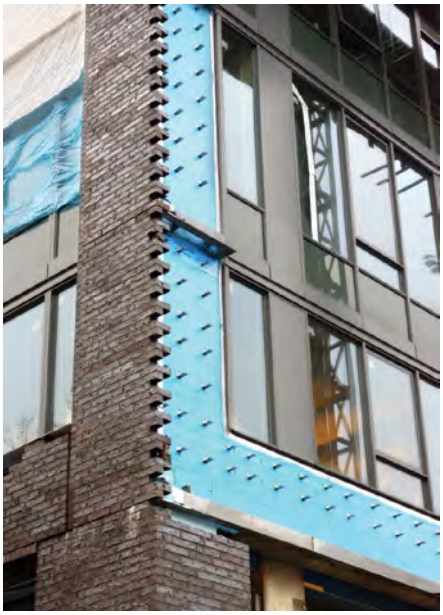


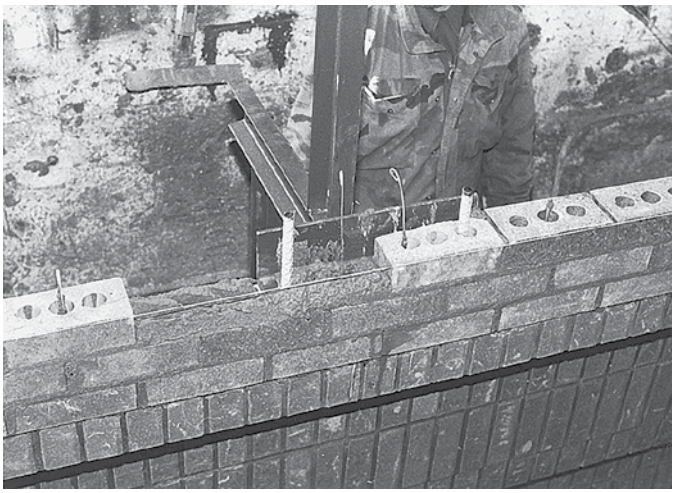
Figure 20.6
Brick veneer curtain wall construction, similar to that shown in section in Figure 20.5, in progress. On the right side of the image, a fluid-applied air and water-resistive barrier membrane has been applied over glass-mat faced gypsum sheathing, and the first halves of two-piece stainless steel masonry anchors have been installed. Next, rigid foam insulation panels will be pushed tight against the air and water-resistive barrier, with the masonry anchors piercing the insulation. As the brick veneer is laid, the second, mating halves of the anchors will be installed and embedded in the brick mortar joints. Two galvanized steel shelf angles can also be seen. *(Photo by Joseph Iano.)*

Prefabricated Brick Panel Curtain Walls

Figure 20.7 shows the use of *prefabricated reinforced brick panels* for cladding. Masons construct the panels while working comfortably at ground level in a dry, climate-controlled factory or shop. Horizontal reinforcing may be laid into the mortar joints or grouted into channel-shaped bricks. Vertical reinforcing bars are placed in grouted cavities of hollow-core bricks. These panels are self-rigid; they need no structural backup and can be fastened to the building in much the same way as precast concrete panels. A steel stud backup wall is required to carry thermal insulation, air barrier, electrical wiring, and an interior finish layer, but it has no structural role.

FIGURE 20.7

Brick panel curtain wall. (*a*) Masons construct the panels in a factory, using conventional bricks and mortar. Both horizontal and vertical reinforcing are used, the vertical bars being grouted into the hollow cores of the bricks. (*b*) Brick panels awaiting shipment, complete with thermal insulation attached. The metal framing is for attachment to the building; the structural strength of the panel comes primarily from the reinforced masonry, not the framing. (*c*) At the construction site, panels are lifted into position by crane. (*d*) Corners can be constructed as single panels. *(Panelized masonry by Vet-O-Vitz Masonry Systems, Inc., Brunswick, Ohio.)*



(*a*)

(*b*)

(*c*)

(*d*)

Stone Curtain Walls

Stone can be attached to buildings in many ways. Stone masonry relying on traditional composite or cavity wall construction is discussed in Chapter 9. For taller buildings, stone veneer can be used as part of cavity wall construction in the same way as brick, as illustrated in the previous section of this chapter.

The stone cladding methods illustrated in the following sections permit larger slabs of stone to be attached to buildings without reliance on a supporting backup wall. Unlike a cavity wall, which functions as a type of drained cladding, these systems resist the passage of water primarily as barrier walls. (See Chapter 16 for more information about keeping water out of walls.)

Stone Panels Mounted on a Steel Subframe

Figure 20.8 shows a system for mounting stone panels on a steel subframe, called *grid-system-supported stone cladding*. The vertical members of the subframe are erected first. They are designed to transmit gravity and wind loads from the stone slabs to the frame of the building. The horizontal members are aluminum shapes that engage slots in the upper and lower edges of each panel to hold them securely in place. They are added as the installation of the stone panels progresses. Backer rods and sealant fill the spaces between the panels, allowing for necessary movement. A nonstructural backup wall, usually made of steel studs and gypsum sheathing panels, is constructed within the frame of the building but is not attached to the subframe. Its functions are to provide an air barrier, to house thermal insulation and electrical wiring, and to support the interior wall finish layer, which is usually gypsum board.

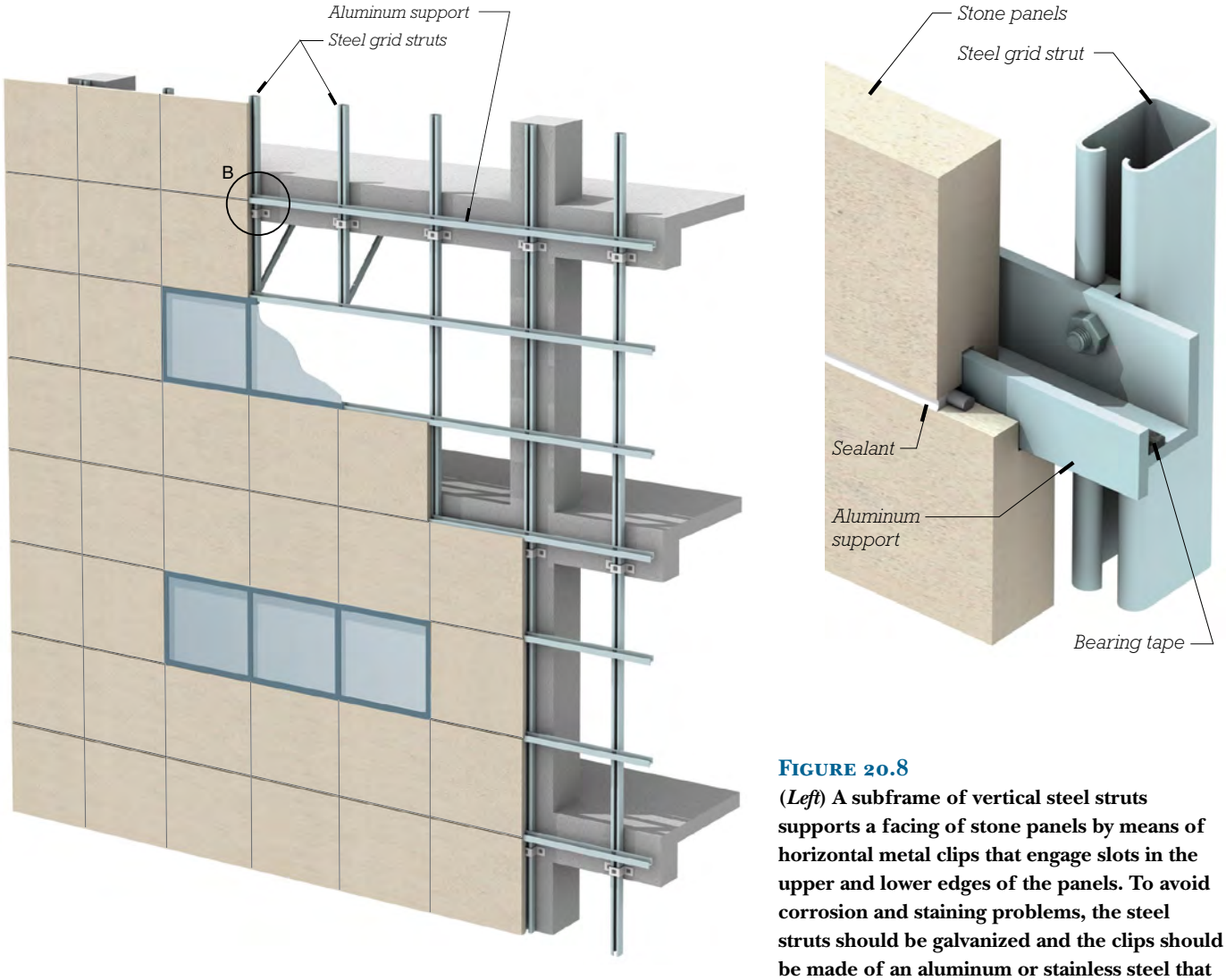
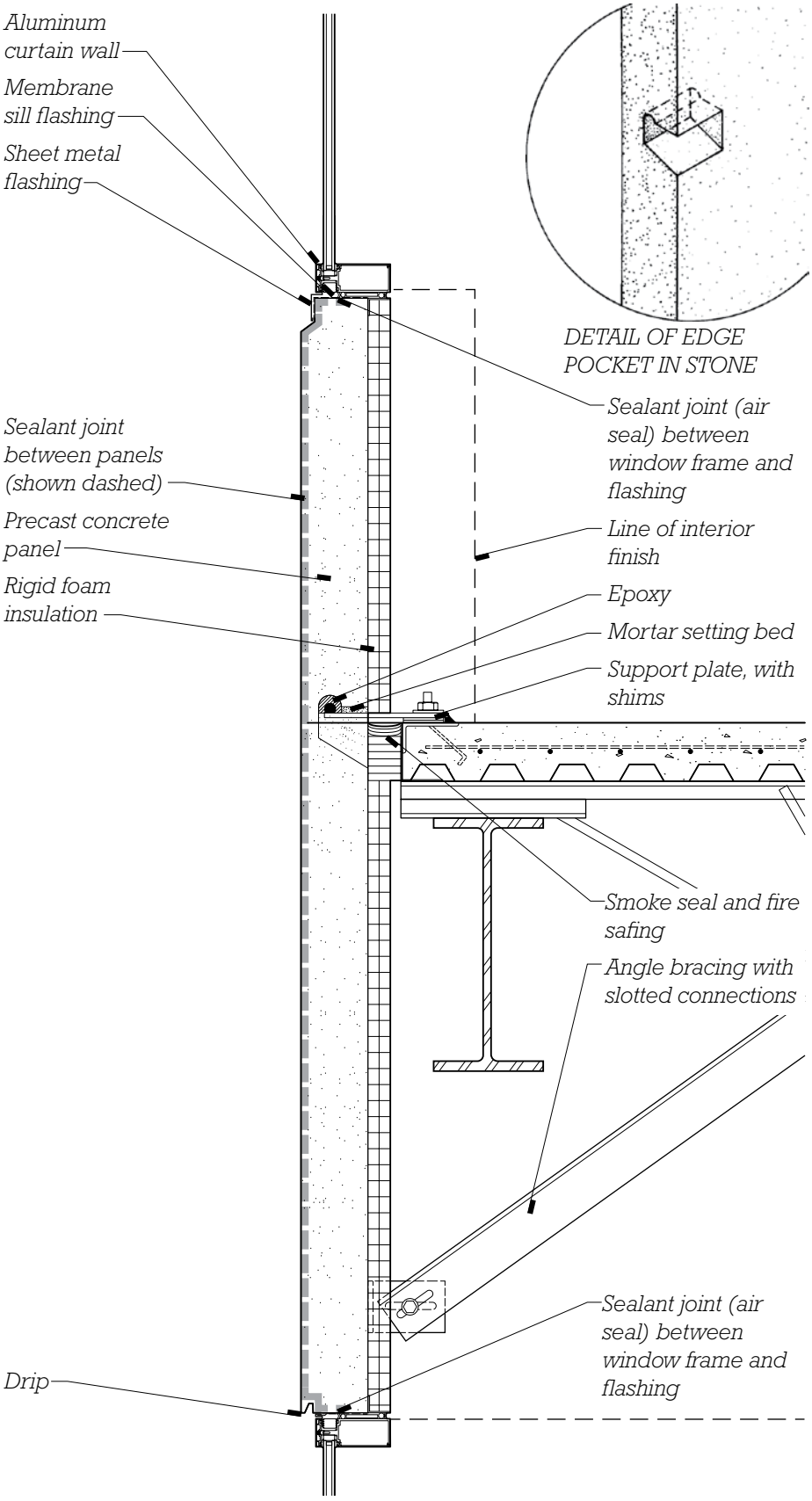


Figure 20.8
(*Left*) A subframe of vertical steel struts supports a facing of stone panels by means of horizontal metal clips that engage slots in the upper and lower edges of the panels. To avoid corrosion and staining problems, the steel struts should be galvanized and the clips should be made of an aluminum or stainless steel that is chemically compatible with the type of stone being used. (*Right*) A detail of the support-to-panel connection.



Monolithic Stone Cladding Panels

Figure 20.9 illustrates a *monolithic stone cladding panel* hung directly off the frame of a building. The weight of the panel is transferred to a pair of steel support plates at pockets that were cut into the back sides of the panel at the stone mill. Angle bracing provides lateral support. The bolted support plates and bracing are designed for quick attachment and easy adjustment. Later, these connections are welded in place to ensure that they do not shift over time. Thermal insulation can be provided with rigid foam boards attached to the back of the panels (as shown), spray foam applied to the back of the panels, or batts added as part of the interior framing and finishes. In colder climates, the first two of these options are preferred, as they reduce the chance of warm, moist interior air reaching the back of the colder panels where condensation can occur.

This installation functions as a barrier wall, blocking the passage of water at the face of the panels. Aside from the flashings around window openings, there is no provision for capturing and redirecting water to the exterior if it penetrates past the face of the wall. The most vulnerable part of this system is the sealant joints between panels, as this material is likely to degrade over time. A more durable way to seal joints between panels such as these, exploiting pressure-equalized design, is illustrated in Figure 20.12 and explained in the text accompanying that figure.

FIGURE 20.9
A stone panel curtain wall made of limestone, marble, or granite. The support plate is made of a galvanized or stainless steel. The smoke seal and fire safing slow the passage of smoke and fire between floors in the event of a building fire. Depending on building size and other factors, fireproofing of the structure or exterior wall may be required (not shown).

Stone Cladding on Steel Trusses

In *truss-supported stone cladding*, sheets of stone are combined into large prefabricated panels by mounting them on steel trusses (Figure 20.10). Each truss is designed to carry both wind loads and the dead load of the stone to connection brackets that transfer these loads to the frame of the building. Sealant joints and a nonstructural backup wall finish the installation.

(*a*)

(*b*)

(*c*)

FIGURE 20.10
A steel truss system for stone cladding. (*a*) Masons working in a fabrication yard attach thin sheets of stone to welded steel trusses. The vertical joints are closed with backer rods and sealant. (*b*) The completed spandrel panel is lifted onto a truck using a crane. The metal clips that are just visible along the top and bottom edges of the panel engage slots in the edges of the sheets of stone to hold the stone securely to the truss. The steel angle clips at the two upper corners of the truss will support the panel on brackets welded to the steel columns of the building frame. (*c*) The panel is installed. *(Courtesy of International Masonry Institute, Washington, DC.)*

Posttensioned Limestone Spandrel Panels

Thick blocks of limestone may be joined with adhesives into long spandrel panels and posttensioned with high-strength steel tendons so that the assembly is self-supporting between columns (Figure 20.11). Such *posttensioned limestone spandrel panels* are relatively costly, because of their use of comparatively large quantities of stone per unit area of cladding.

Thin Stone Facings

Very thin sheets of stone, as little as ¼ inch, or 6.5 mm for granite, may be stiffened with a structural backing such as a composite metal panel and mounted as spandrel panels in an aluminum mullion system, such as one of those described in Chapter 21.

Thin sheets of stone may also be used as facings for precast concrete curtain wall panels. The stone sheets are laid face down in the forms. Stainless steel clips are inserted into holes drilled in the backs of the stone. A grid of steel reinforcing bars is added, and then the concrete is poured and cured to complete the panel. The clips anchor the stone to the concrete.

When determining acceptable minimum thickness for any particular stone and application, stone industry standards, supplier recommendations, chemical analysis, physical testing, and past experience with particular stone products may all be taken into consideration.

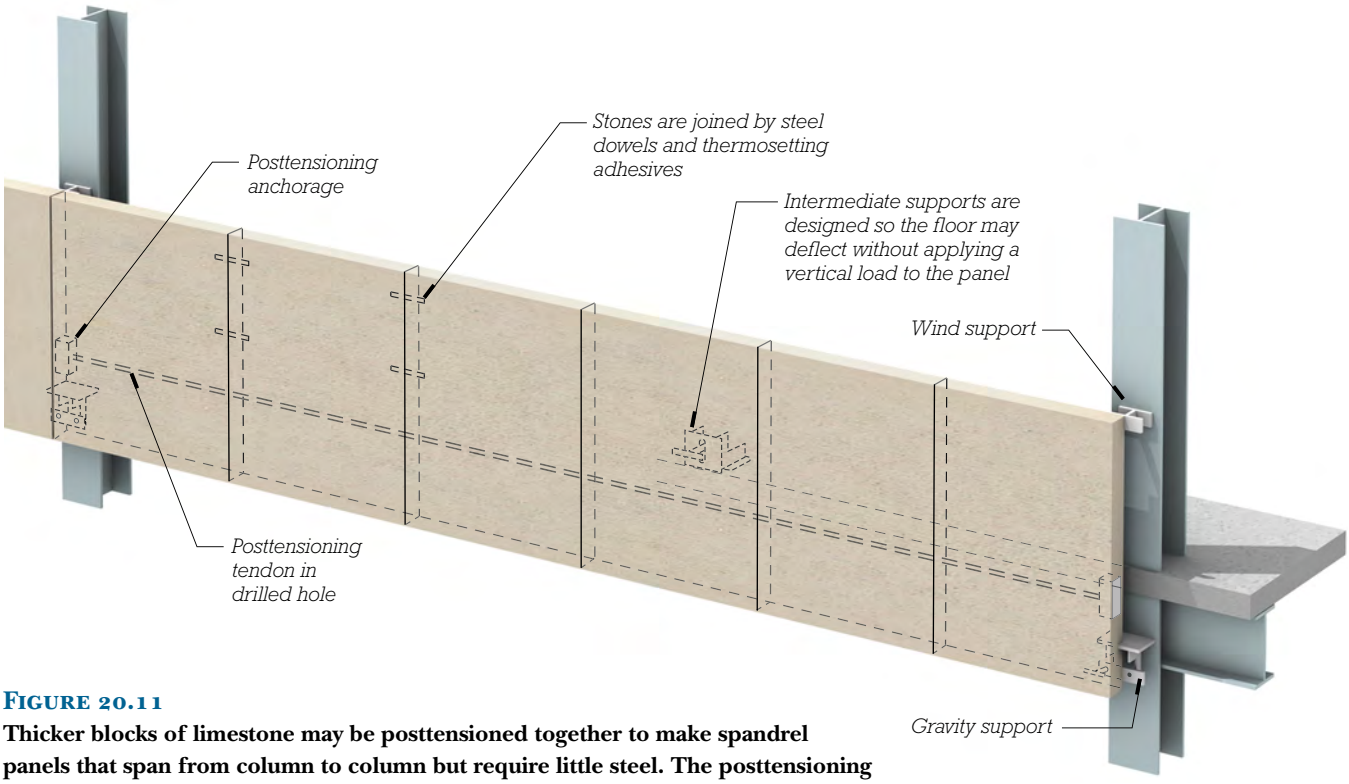
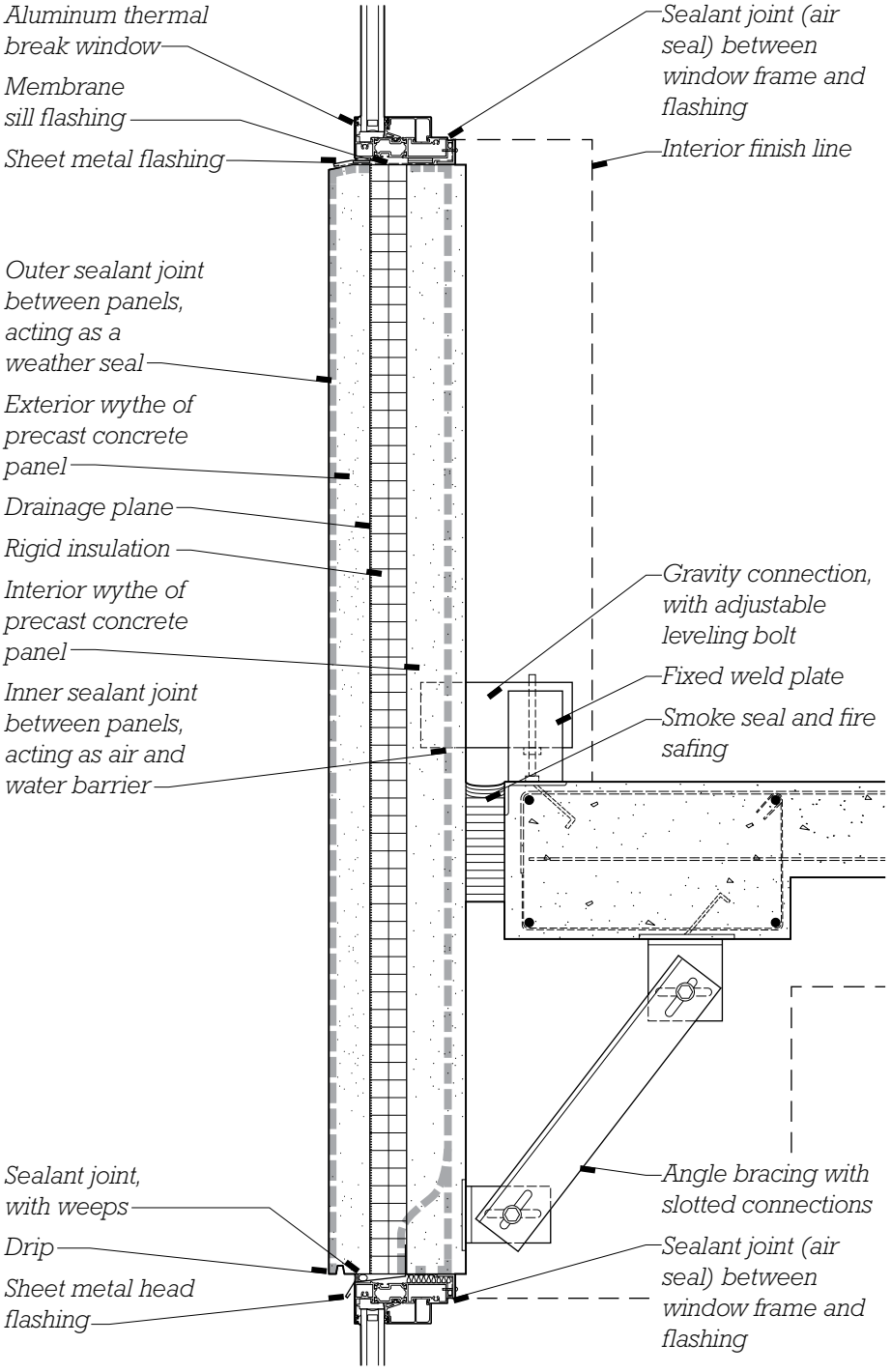


FIGURE 20.11
Thicker blocks of limestone may be posttensioned together to make spandrel panels that span from column to column but require little steel. The posttensioning tendon is threaded through matching holes that are drilled in the individual stones prior to assembly.

FIGURE 20.12
(*Opposite page*) A precast concrete sandwich panel installation, designed as a drained cladding system (panel reinforcing is not shown). To create a drainage plane within the panel, a thin drainage mat is inserted between the outer wythe of concrete and insulated core, or insulation boards with vertically grooved faces may be used. At the vertical joints between panels, two lines of joint sealant (shown dashed) create a pressure-equalized space that neutralizes wind pressures that could otherwise drive water through the joint. The connections between the panel and building structure are designed to allow for easy adjustability during installation. Once the panel is in final position, welds are added to provide greater strength and prevent future slippage.

Precast Concrete Curtain Walls

Precast concrete cladding panels (this chapter's opening photograph, and Figures 20.12 through 20.14) are produced in the factory using high-quality molds. Panel surfaces can be flat or heavily profiled, with exposed finishes ranging from glassy smooth to rough and heavily textured. Ceramic tile, thin brick, or thin stone may also be bonded to the face of the panels. Precast concrete panels may be conventionally reinforced or prestressed and are designed to resist the wind, gravity, seismic, and lifting forces to which they are exposed. Attachments, in the form of various steel components, transfer these forces to the building frame while allowing for adjustment during installation. *Precast concrete sandwich panels* (Figure 20.12) incorporate thermal insulation within the panel. When solid panels are used, insulation may be affixed to the back of the panel or provided in a nonstructural backup wall that is constructed in place. Carbon fiber reinforcing (Chapter 15) or ultra-high performance concrete (Chapter 13) are also used to create panels that are thinner and lighter than those made of traditional materials.



Like monolithic stone cladding, precast concrete panels are attached to the building frame without the need for a supporting backup wall. The panel installation in Figure 20.12 illustrates a drained cladding system. Within the panel itself, a drainage plane is created between the back of the outer concrete wythe and the insulation. At the vertical joints between panels, two sealant joints are used. The outer *weather seal* acts as the first line of defense against water penetration, but is not expected to remain perfectly watertight over the life of the cladding system. Further back in the panel joint is a second sealant joint, protected from sunlight and temperature extremes, that acts as both an air barrier and the second line of defense against water ingress. Together, these create a pressure-equalized joint that reliably prevents the passage of water. Water captured within the panel or joints falls downward and is directed back to the exterior by the head flashing at the panel bottom. Additional flashings around the jamb and sill of the panel opening capture and redirect to the exterior any water that penetrates between the window and panel.

This figure also illustrates the principles of air barrier continuity within a wall system. The inner wythe of the sandwich panel acts as the air barrier in the panel itself. Between panels, continuity of the air barrier

FIGURE 20.13
A precast concrete cladding panel rests on a flatbed truck, waiting to be lifted into place and attached to the building frame. A pair of braced connections, which will support the weight of the panel once it is installed, are visible on the backside of the panel. These are made of galvanized hollow steel sections with adjustable leveling bolts. The panel is upside-down relative to its installed position. *(Photo by Joseph Iano.)*

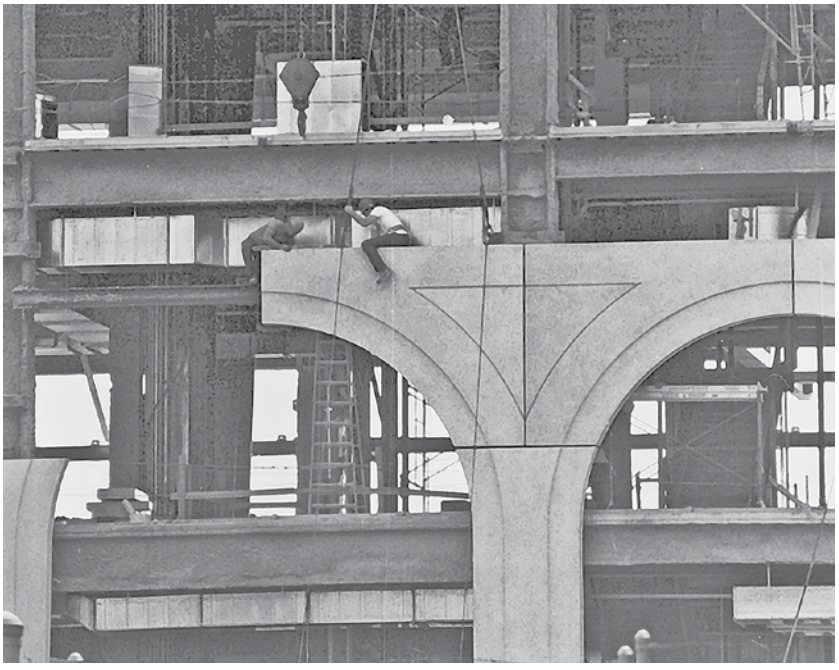


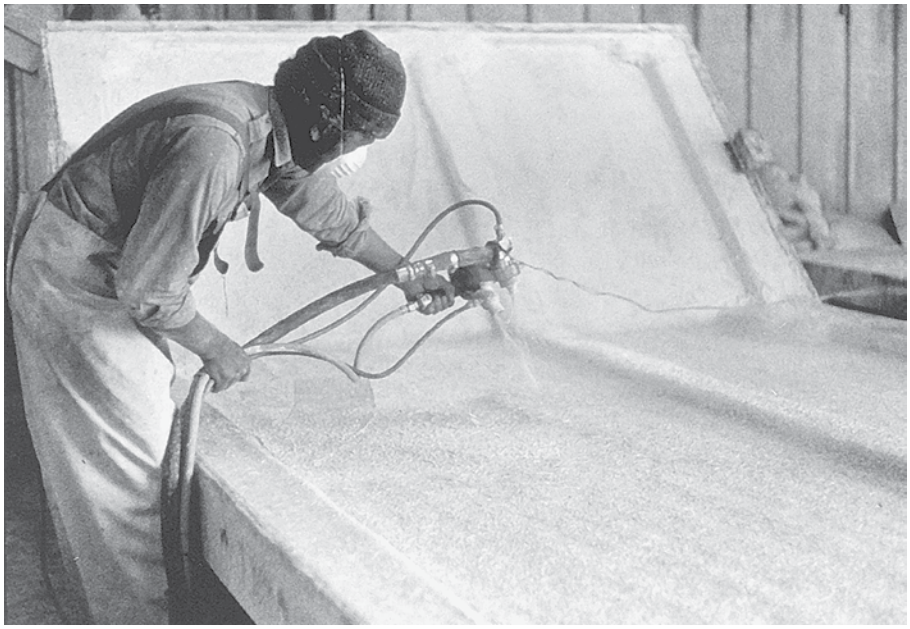
FIGURE 20.14
Workers install a precast concrete curtain wall panel. *(Architect and engineer: Ander-Nichols Company, Inc. Photo by Edward Allen.)*

is maintained by the inner joint seals that span between panels. Between panels and the windows, air barrier continuity is maintained by the flashings that seal against the inner panel wythes and the joint seals (air seals) between flashing and window frame.

Glass-Fiber-Reinforced Concrete Curtain Walls

Glass-fiber-reinforced concrete (*GFRC*) has several advantages over conventional precast concrete panels. Its admixture of short glass fibers furnishes enough tensile strength that no steel reinforcing is required. Panel thicknesses and weights are about one-quarter of those for conventional precast concrete panels, which saves money on shipping, makes the panels easier to handle, and allows the use of lighter attachment hardware. The light weight of the cladding also allows the loadbearing frame of the building to be lighter and less expensive. GFRC can be molded into three-dimensional forms with intricate profiles and an extensive range of colors and textures (Figure 20.15).

The fibers in GFRC must be manufactured from a special alkali-resistant type of glass to prevent their disintegration in the concrete. The panels may be self-stiffened with GFRC ribs, but the usual practice is to attach a welded frame made of light gauge steel studs to the back of each GFRC facing in the factory. The attachment is made by means of thin steel rod anchors that flex slightly as needed to permit small amounts of relative movement between the facing and the frame (Figure 20.16).



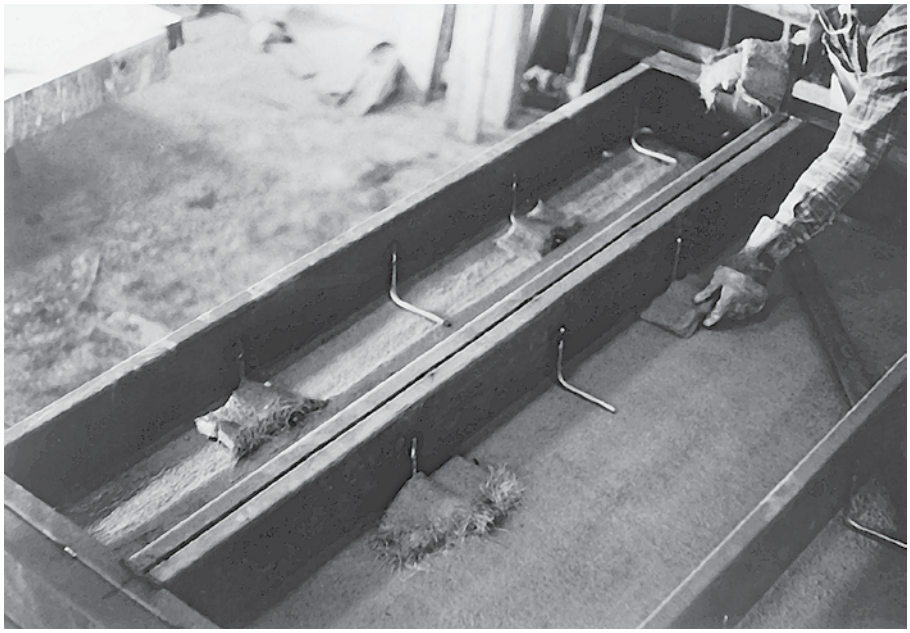


FIGURE 20.15
Fabrication of a GFRC curtain wall panel. (*Top*) A special gun deposits a layer of sand–cement slurry simultaneously with 1.5-inch (38-mm) lengths of alkali-resistant glass fiber reinforcing. Three layers are usually required to make up the full thickness of the panel facing; each is compacted with a small hand roller before the next layer is applied. The overall thickness is usually ½ inch (13 mm). (*Bottom*) After the GFRC facing layer has been completed, the steel frame is lowered over it and the operator hand-applies pads of wet GFRC over the rod anchors to bond the frame to the GFRC facing. *(Courtesy of Precast/Prestressed Concrete Institute.)*

Exterior Insulation and Finish Systems

An *exterior insulation and finish system* (*EIFS*) consists of an insulation board that is adhered or mechanically fastened to a backup substrate, a reinforcing mesh that is applied to the outer surface of the insulation by embedment in a base coat of a stuccolike material, and an exterior finish coat of a similar material that is troweled over the reinforced base coat. In most cases the substrate is concrete masonry or site-erected steel studs covered with water-resistant sheathing (Figures 20.17, 20.18, and 20.19). The system also adapts readily to prefabrication.

EIFS is a versatile type of cladding. It is used for building types as diverse as wood light-frame single-family residences and large buildings of noncombustible construction. It can be used for both new construction and the refacing and insulating of existing buildings. Insulation boards may be made of plastic foam or, where combustibility of the cladding is a concern, mineral wool. The base coat plaster may consist of portland cement or synthetic polymers. By varying the base coat plaster formulation, along with its thickness, type of reinforcing, and number of layers of application, varying degrees of toughness and resistance to impact can be achieved. EIFS finish coats may also be formulated from portland cement, but most often are acrylic or other polymer. They can be applied in a wide range of colors and textures, and made to resemble, at least from a distance, conventional stucco, precast concrete, or even brick or stone masonry. EIFS is also a thermally efficient cladding system, as it provides a continuous layer of exterior insulation up to 4 inches (100 mm) thick, with little to no thermal bridging.

In its original configuration, North American EIFS was designed to control the passage of exterior water as a barrier wall system. However, when water did penetrate past the outer finish coat, it could become

Figure 20.16
Partially completed GFRC cladding for the Beirut Souks, designed by Zaha Hadid Architects with Samir Khairallah & Partners. Additional stockpiled panels, ready for installation, are partly visible in the foreground of the image. *(Photo by Joseph Iano.)*

entrapped and cause damage within the cladding system or to the substrate to which it was attached. Today, such a *barrier-wall EIFS* has been largely replaced by a *water-managed* or *drainage-wall EIFS*. In these drained cladding systems, a water-resistive barrier membrane is applied over the substrate behind the EIFS and a shallow drainage space is created between the barrier membrane and the insulation board. In this way, water that does penetrate the cladding can drain downward and back to the exterior through weeps provided at the base of each panel. The most common way to create the drainage space behind the insulation is by applying the insulation adhesive in vertical strips, with the gaps remaining in between acting as drainage channels. Alternatively, insulation boards with integral vertical channels may be used, or a thin drain mat may be installed (Figure 20.18). (For more information about barrier wall and drained cladding systems, see Chapter 16.)

The International Building Code requires water-managed systems wherever EIFS is applied over wood light

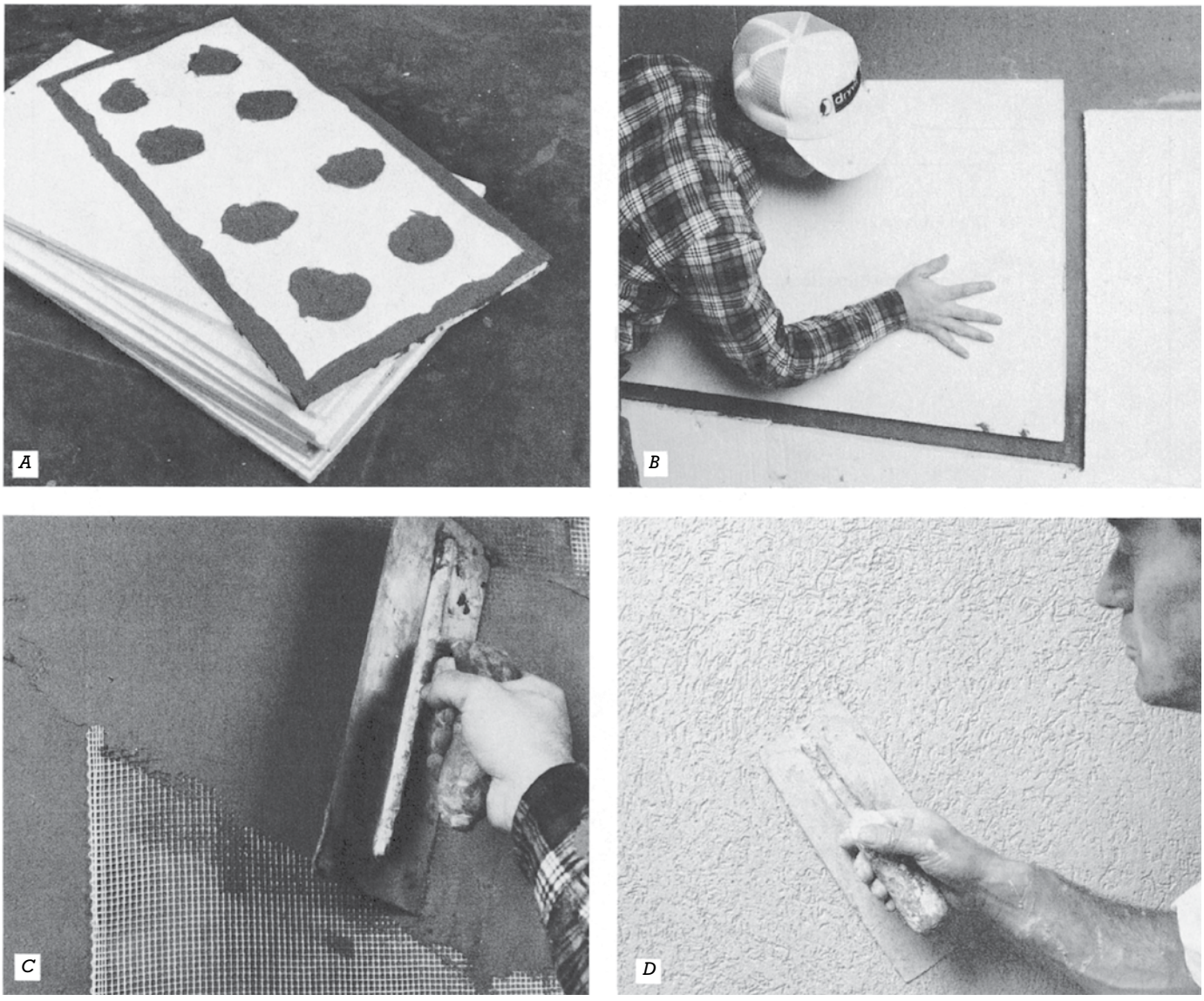


FIGURE 20.17

The four steps in installing EIFS over a building with walls of masonry or solid sheathing. (*A*) A panel of foam is daubed with polymer-modified portland cement mortar. The foam may be as thick as required to achieve the desired thermal performance. (*B*) The foam panel is pressed into place, where it is held permanently by the adhesive mortar. (*C*) A thin base coat of polymer-modified stucco is applied to the surface of the foam panels, with an embedded mesh of glass fiber to act as reinforcing. (*D*) After the base coat has hardened, a finish coat in any desired color is troweled on. *(Used with permission of Dryvit® Systems, Inc.)*

frame buildings of any multifamily residential occupancy type. On tall buildings, EIFS must also pass the same tests demonstrating resistance to ignition and flame spread as other cladding materials, minimizing the risk of large-scale fire on the exterior faces of such buildings.

FIGURE 20.19
An early 20th-century warehouse, reclad with EIFS to improve its energy efficiency and renew its appearance. *(Photo by Joseph Iano.)*

FIGURE 20.18
A mockup demonstrates the features of a water-managed EIFS. From interior to exterior, the layers are a water-resistant substrate board, an asphalt-saturated felt water-resistive barrier, a drainage mat composed of plastic fibers, plastic foam insulation, reinforcing mesh, a base coat, and a finish coat. A continuous plastic flashing under a gap at the bottom of the wall drains any leakage out to the face of the wall. Fluid-applied or adhered sheet membranes that can act as air and water barriers are also frequently used in place of the building felt shown here. *(Photo of the Senergy CD System, courtesy of Senergy, Cranston, RI.)*

MasterFormat Sections for Cladding with Masonry and Concrete

03 45 00	**PRECAST ARCHITECTURAL CONCRETE**
03 45 13	Faced Architectural Precast Concrete
03 49 00	**GLASS-FIBER-REINFORCED CONCRETE**
04 27 00	**MULTI-WYTHE UNIT MASONRY**
04 27 23	Cavity Wall Unit Masonry
04 42 00	**EXTERIOR STONE CLADDING**
04 42 16	Steel-Stud-Supported Stone Cladding
04 42 23	Truss-Supported Stone Cladding
04 42 26	Grid-System-Supported Stone Cladding
04 42 43	Stone Panels for Curtain Walls
07 24 00	**EXTERIOR INSULATION AND FINISH SYSTEMS**
07 24 19	Water-Drainage Exterior Insulation and Finish Systems

Key Terms

masonry veneer
cavity
backup wall
shelf angle
knife plate
structural thermal break
through-wall flashings
smoke seal
fire safing
horizontal expansion joint, soft joint
vertical expansion joint
prefabricated reinforced brick panels
grid-system-supported stone cladding
monolithic stone cladding panel
truss-supported stone cladding
posttensioned limestone spandrel panel
precast concrete cladding panel
precast concrete sandwich panel
weather seal
glass-fiber-reinforced concrete (GFRC) cladding panel
exterior insulation and finish system (EIFS)
barrier-wall EIFS
water-managed EIFS, drainage-wall EIFS

Review Questions

1. List all the common ways of attaching stone cladding to a building. Make a simple sketch to explain each system.
2. Working from memory, sketch all the details of a brick veneer wall over a concrete or steel structural frame.
3. What are some options of surface finishes for precast concrete cladding panels?
4. Describe the process of producing GFRC panels, illustrating your account with simple sketches.
5. Name two types of EIFS and explain each.

Exercises

1. Design and detail a brick veneer cladding for a multistory building that you are designing. Rather than trying to conceal the flashings and soft joints, work out a way of expressing them boldly as part of the architecture of the building.
2. Visit one or more buildings under construction that are being clad with masonry, concrete, GFRC, or EIFS. Make sketches of how the materials are detailed, especially how they are anchored to the building. What will happen to any water that leaks through the cladding?
3. Create a 3D representation of a precast concrete curtain wall system. Illustrate the continuity of the air, water, and thermal control layers.

Selected References

All the references on stone and concrete masonry listed at the end of Chapter 9 are also relevant to this chapter.

Brick Industry Association. "Technical Notes on Brick Construction," Nos. 17L, 27, and 28B. Reston, VA, various dates.

These detailed pamphlets cover every aspect of brick veneer cladding systems.

Precast/Prestressed Concrete Institute. *Architectural Precast Concrete* (3rd ed.). Chicago, 2007.

This is a well-illustrated hardbound book that covers all aspects of the design, manufacture, and installation of precast concrete curtain walls. Also available from the same source is *Architectural Precast Concrete—Color and Texture Selection Guide* (2003), which provides an extensive set of full-color plates of finishes for precast concrete panels.

Precast/Prestressed Concrete Institute. *GFRC: Recommended Practice for Glass Fiber Reinforced Concrete Panels* (4th ed.). Chicago, 2001.

This 104-page booklet is a clear, complete guide to the design and manufacture of GFRC cladding systems.

Websites

Brick Industry Association: www.gobrick.com

Dry-Vit Systems: www.dryvit.com

EIFS Industry Members Association: www.eima.com/eifs

Natural Stone Institute: www.buildingstoneinstitute.org

Precast/Prestressed Concrete Institute: www.pci.org

Whole Building Design Guide, Precast Concrete Wall Systems: www.wbdg.org/guides-specifications/building-envelope-design-guide/wall-systems/precast-concrete-wall-systems

Whole Building Design Guide, Thin Stone Wall Systems: www.wbdg.org/guides-specifications/building-envelope-design-guide/wall–systems/thin-stone-wall-systems

CASE STUDY: Seattle University School of Law

ARCHITECT: Olson Sundberg Kundig Allen Architects

ASSOCIATED ARCHITECT: Yost Grube Hall Architecture

STRUCTURAL ENGINEER: Putnam Collins Scott Associates

When Seattle University founded its new school of law, it commissioned Olson Sundberg Kundig Allen Architects to design the program's new home. The university wanted a building that would give the school prominence on the campus and one that would both fit within the context of existing masonry structures and reflect the modern roots of this newly instituted program (Figure A).

In response, the architects chose a building cladding system combining brick veneer and aluminum curtain wall—a balance of old and new materials. As the design took shape, they also strove to design and detail the veneer in such a way as to express the modern, skin-like qualities of this cladding system. Brick panels were to be arranged in horizontal bands, visibly supported on structural steel channels. Integrated exterior steel sunshades would reinforce the ribbonlike character of the system.

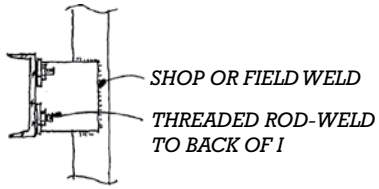
An important decision came when the architects had to design the veneer's steel channel supports. One option was to support the brick with steel shelf angles concealed behind the veneer and then add a visible channel shape that would express the loadbearing function while not actually acting in a structural role. The second option was to design the steel channel as the means of veneer support, allowing the channel to perform in both the architectural and structural roles.

There were pros and cons to both options. The first option relied on a more conventional method of construction, one that would be easier to communicate to the builder. In addition, because the channel would be nonstructural, it could be fabricated from materials that would be lighter and would accept a wider range of finish options, such as sheet metal formed to imitate the shape of a structural channel. However, a structural channel would have a

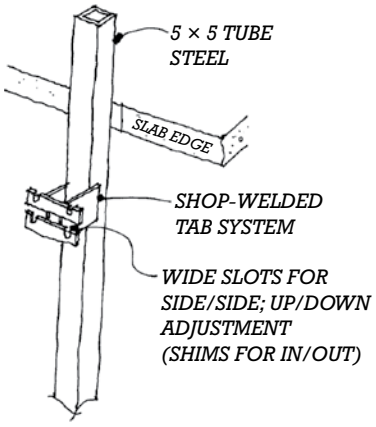
FIGURE A

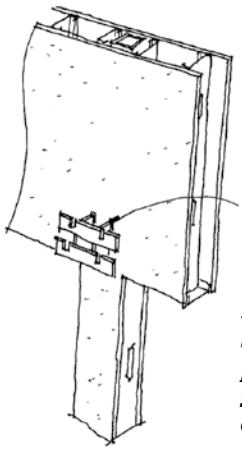
Seattle University School of Law.

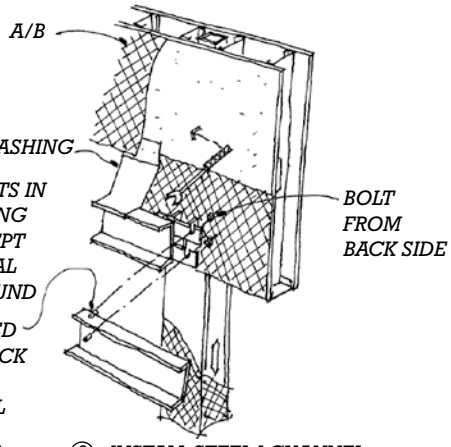
FIGURE B
Assembly sequence studies.



CROSS-SECTION DETAIL

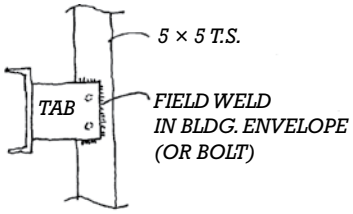




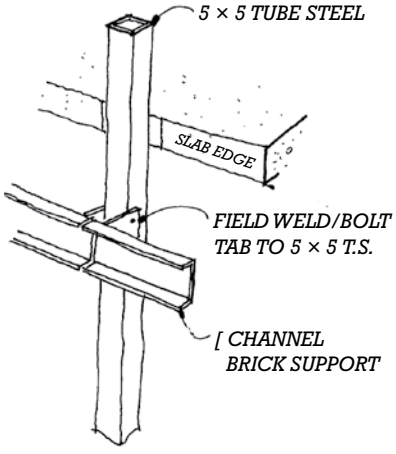


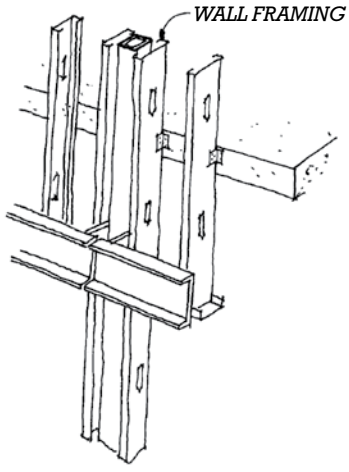
① ERECT STRUCT. STEEL ② ERECT WALL FRAMING/SHEATHING ③ INSTALL STEEL I CHANNEL

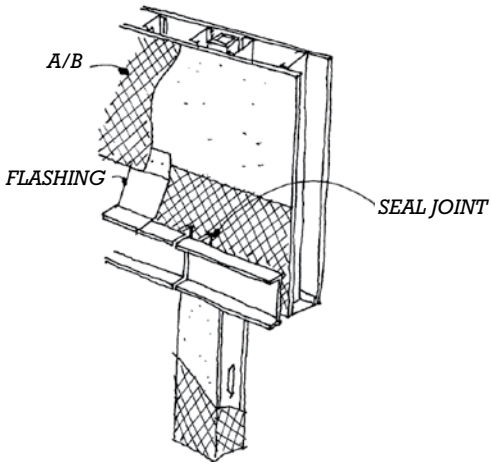
BRICK LEDGER CHANNEL CONSTRUCTION "A"



CROSS-SECTION DETAIL







① ERECT STRUCT. STEEL ② ERECT WALL FRAMING ③ SHEATHING

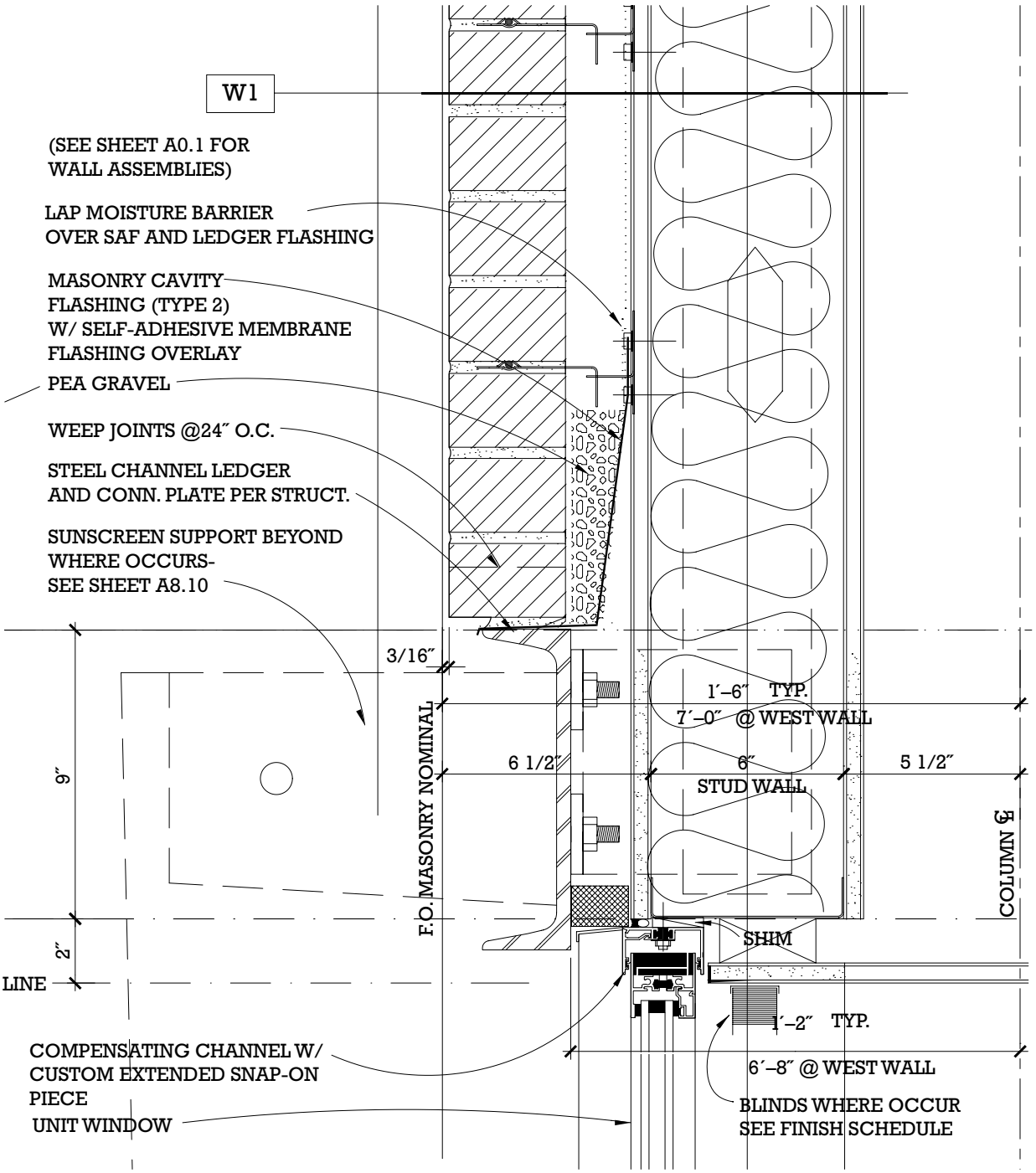
BRICK LEDGER CHANNEL CONSTRUCTION "B"

heavier and more genuine appearance. It would not be at risk of being seen as an unnecessary adornment that could be removed from the project as a budget-cutting measure. To the architects, this second option seemed a more authentic way to express the weight of the veneer and its means of support.

If the second option was to be considered, the architect needed to validate this unconventional method of veneer support. Working with the structural engineer, design of the channel and options for its attachment to the building frame were studied (Figure B). Sequences of assembly were explored to verify that the various building systems, including the structural frame, steel stud backup, sheathing, exterior enclosure materials, and veneer, could be erected in a logical way. These studies convinced the design team that the structural channel was practical, and the decision was made to proceed with this option. The final construction drawings showed a structural steel channel blind bolted to connection plates that were, in turn, welded to the structural steel frame (Figure C).

Figure C

Construction drawing set detail.



As expected, extra effort was required on the part of the architect to address questions that arose during construction. One issue concerned the sequence of assembly. After studying various options during the design phase, the architect had completed the design and detailing based on the assumption that the supporting channels would be erected along with the brickwork, after the backup steel studs and sheathing had been put in place. The contractors based their construction schedule on attachment of the structural channels much earlier in the process, at the same time as the erection of the structural steel frame. Though both methods were feasible, adopting this alternative sequence required the architect to revise other parts of the construction documents to coordinate the effects of this change with other aspects of the exterior wall assembly.

A second difficulty was related to maintaining erection tolerances for the structural channels. The channel supports had to be located with sufficient precision to achieve the dimensional accuracy required by the brickmasons for their work. Recognizing that tolerances for the placement of the structural steel columns were significantly greater than could be allowed for the channels themselves, attachments between the columns and channels had been designed to allow for adjustability between these elements. Despite these preparations, column misalignments in the field in some cases exceeded the limits of adjustment that had been designed into the connections.

This problem was compounded by unanticipated irregularities in the channels themselves. The channels had been specified to be hot-dip galvanized, a process by which a heavy zinc coating is applied to the steel to protect against corrosion. Heating of the channels during the hot-dip process caused them to warp subtly. Although not sufficient to make the channels unusable, this added distortion made it even more difficult to mount the channels on the columns with the required precision. To solve these problems, the connection design was revised to allow welding as an alternative to the original bolted design, thereby permitting greater adjustability. In the end, constructional difficulties were resolved, the brick veneer was successfully completed, and the final wall system achieved the functional and architectural goals of both the client and the architect. This project illustrates the important role that planning for constructability can play in the smooth and successful outcome of a project and the realization of the project's design goals.

Figure D
Photo detail of veneer and channel support.

21

Cladding with Metal and Glass

- **Aluminum**
  - Aluminum Alloys
  - Aluminum Extrusion
  - Thermal Breaks

Sustainability and Cladding with Metal and Glass

  - Surface Finishes for Aluminum
  - Other Curtain Wall Frame Metals
- **Aluminum and Glass Framing Systems**
  - Modes of Assembly
  - Water Management
  - Allowing for Movement
  - Outside and Inside Glazing
- **An Outside Glazed Curtain Wall System**
- **Double-Skin Facades**
- **Sloped Glazing Systems**
- **The Curtain Wall Design Process**
- **Metal Panel Cladding**

The faceted planes and diamond-patterned mullions of the Seattle Public Library create a striking geometrical composition. The makeup of the double glazing varies depending on exposure. Where the highest thermal efficiency is required, units include krypton gas fill and low-e coating. Where the potential for solar heating is greatest, an aluminum expanded metal mesh interlayer reduces solar transmission. Structural steel, framed to mirror the diamond pattern, carries the weight of the curtain wall and resists wind loads. *(Architect: OMA/LMN; curtain wall design build: Seele. Photo by Joseph Iano.)*

The contemporary metal-and-glass curtain wall is a descendant of the cast-iron-and-glass walls that were common features of commercial buildings in the 19th century. Today's walls, however, are vastly more sophisticated in every respect. They are carefully isolated from the frame of the building so that they support only their own weight and the forces of the wind. They are insulated and thermally broken to maximize comfort and minimize heating and cooling costs and moisture condensation. They utilize advanced glazing and spandrel materials that offer precise control of luminous and thermal properties. They are carefully gasketed and drained to discourage water leaks. Their intricate inner features are concealed behind smooth snap-on covers. They are designed for easy, forgiving installation and maintenance. And they are made of light and strong aluminum, in the form of sleek extrusions that glisten with long-lasting anodized or organic finishes.

Aluminum

Aluminum is the material of choice for metal cladding systems: It is light in weight, protects itself against corrosion, accepts and holds a variety of attractive surface finishes, and can be economically fabricated into elaborate, precise shapes.

Aluminum is the third most plentiful element in the earth's crust. The raw material source for manufactured aluminum is *bauxite*, an ore containing roughly 50 percent aluminum oxide. Bauxite is extracted from the earth, and in the first refining step, mixed with sodium hydroxide (lye). This bauxite–lye slurry is baked under pressure and filtered to extract the aluminum oxide. In the second step, large quantities of electricity are run through the aluminum oxide within large vats called reduction pots. The oxide melts and oxygen atoms are driven off, a process called *smelting*. After further steps to remove impurities, molten aluminum is poured into water-cooled molds, where it hardens into various shapes and sizes, ranging from small 15-pound (7-kg) ingots to massive 30-ton (30-tonne) slabs.

Aluminum Alloys

During the aluminum manufacturing process, small amounts of other elements are added to pure aluminum to produce *alloys* with varying properties. Aluminum alloys are broadly grouped into Series 1 through Series 7, according to the alloying elements used. Most construction industry products are manufactured from alloys in the Series 3, 5, and 6 groups (Figure 21.1).

A complete description of an aluminum alloy includes a four-digit alloy number followed by a *temper* designation identifying the processes used to control strength, hardness, corrosion resistance, and other mechanical properties. For example, 6063–T6 is an alloy used in the manufacture of aluminum doors, windows, and curtain wall. This is a Series 6

Alloy Group	Primary Alloying Elements	Method of Tempering	Common Uses in Building Construction
Series 3xxx	Manganese	Cold working	Aluminum sheet and plate
Series 5xxx	Magnesium	Cold working	Anodized aluminum sheet and plate
Series 6xxx	Silicon, magnesium	Heat treatment	Extruded aluminum products

Figure 21.1
Aluminum alloys commonly used in the manufacture of building components. Series 3 and 5 alloys are tempered by cold working (subjecting the metal to mechanical stress). Series 6 alloys are tempered by heat treatment.

alloy well-suited to extrusion, a forming process discussed in the next section. The T6 temper designation refers to a series of heat treatments used to adjust the microstructure of the aluminum, producing, in this case, a finished metal with medium strength, high corrosion resistance, and good weldability.

Aluminum Extrusion

The principle of *extrusion* is easily visualized: It is like squeezing toothpaste from a tube. In response to the squeezing pressure, the tube produces a column of toothpaste that is cylindrical in shape because the orifice of the tube is round. If the shape of the orifice were changed, one could produce many other shapes of toothpaste as well—square, triangular, flat, and so on (Figure 21.2).

The manufacture of aluminum extrusions begins with the alloying of pure aluminum, casting of the aluminum into solid cylindrical *logs* roughly 20 to 30 feet (6 to 9 m) long, and further heat treatment of the logs to improve their extrudability. Finally, the logs are cut into 20- to 50-inch (500- to 1200-mm) lengths, called *billets*, which are ready for the extrusion process.

To begin extrusion, a billet is reheated to a temperature at which the metal flows under pressure but still retains its shape when the pressure is released (around 1000 degrees Fahrenheit, or 500°C). The heated billet is placed in the cylinder of a large press where a piston squeezes it under enormous pressure (as high as 100,000 psi, or 700 MPa) through a *die*, a steel plate with a shaped metal orifice. The orifice imparts its shape to a long extruded column of aluminum that is supported on rollers, tempered, straightened, and cut into convenient lengths (Figure 21.3).

Very intricate aluminum sections can be extruded for a wide range of purposes, including not only curtain wall components but also door frames, window frames, handrails, grillwork, and structural shapes such as wide flanges, channels, and angles. The high precision of the extrusion process permits it to be used for close-tolerance details as well, such as snap-in glazing beads, snap-on mullion covers, *shear blocks*, *screw slots*, and *screw ports* (Figure 21.4). Hollow shapes may be extruded by mounting the portion of the die that forms the interior of the shape on a steel "spider" that is attached to the inside of the die. The metal flows around the legs of the spider and then merges back together as it passes through the orifice. Extrusion dies are easily produced for custom-designed sections if the production run will be long enough to amortize their expense.

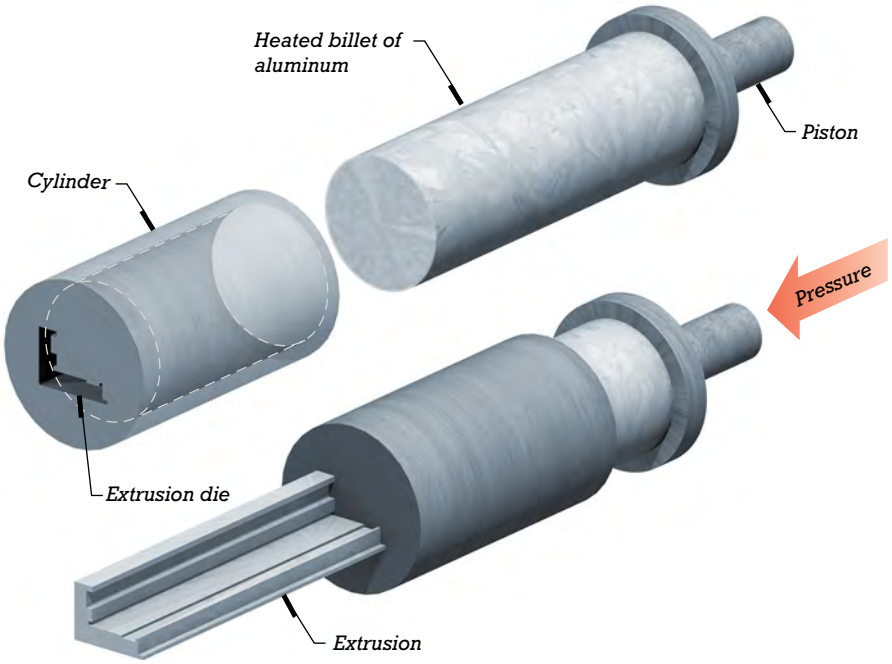
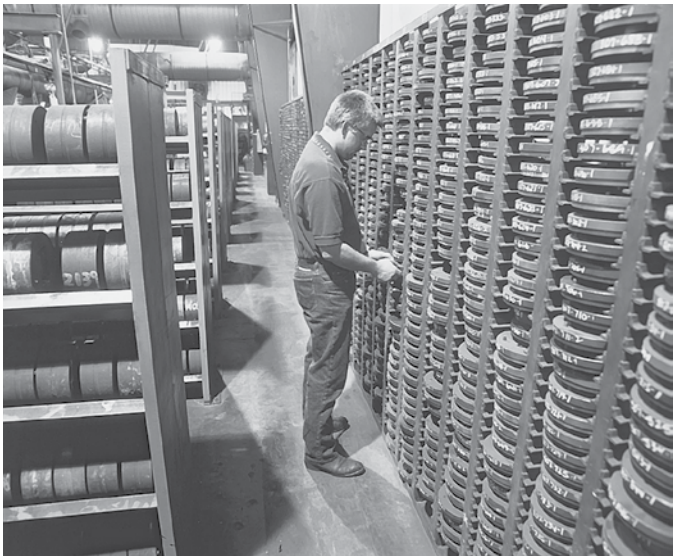
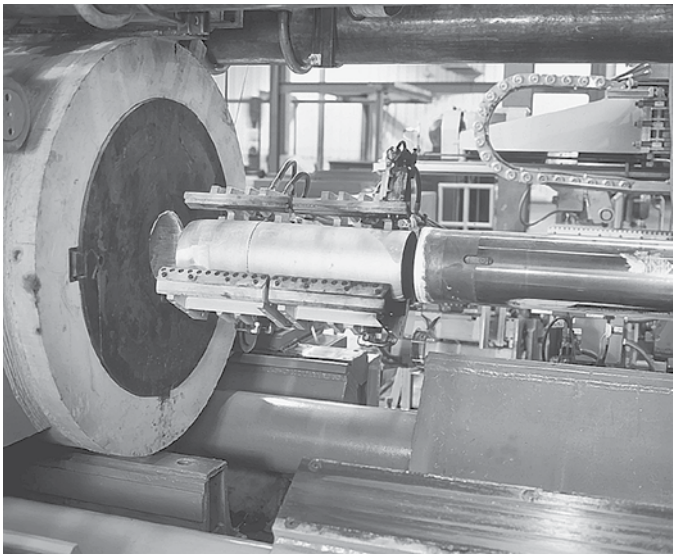


FIGURE 21.2
The concept of extrusion.

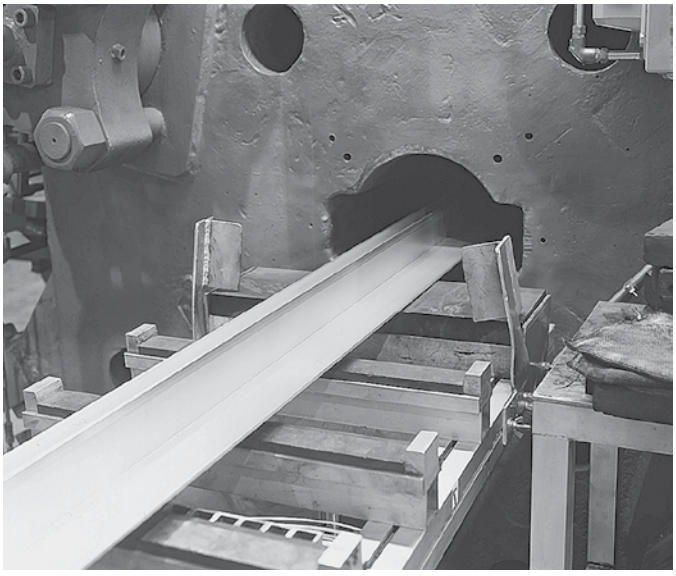
Interactive Exercise



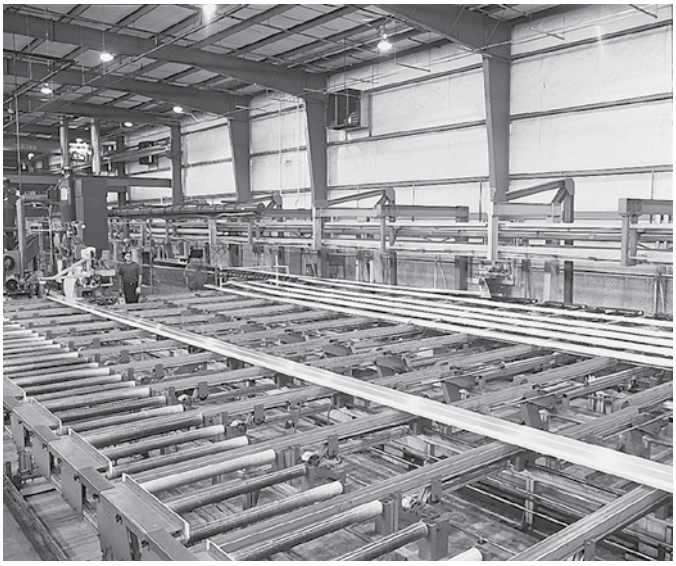
(*a*)



(*b*)

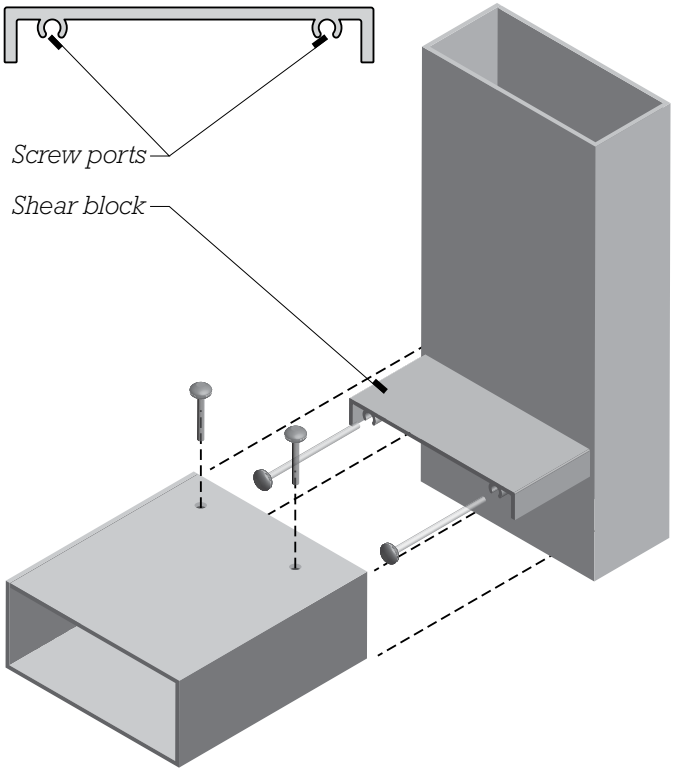


(*c*)

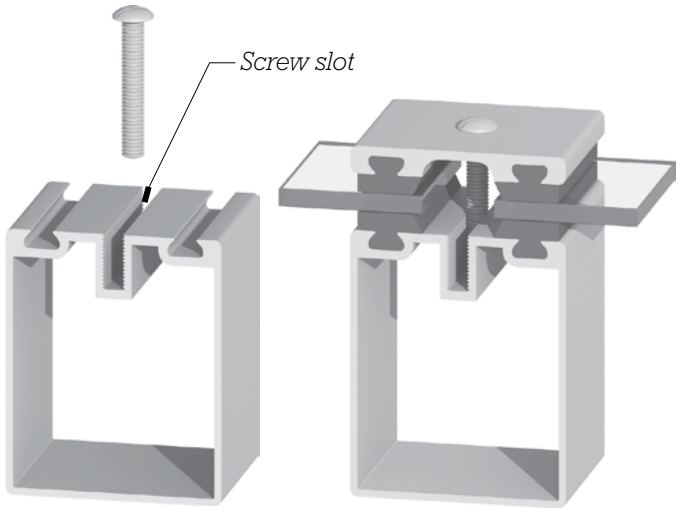


(*d*)

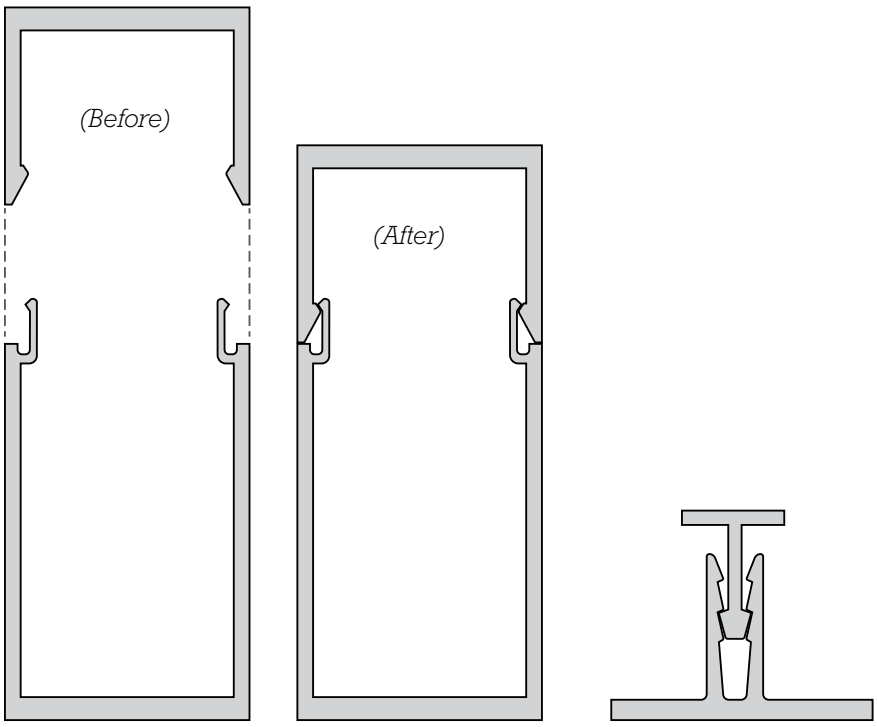
FIGURE 21.3
Making aluminum extrusions for curtain wall components. (*a*) Hundreds of extrusion dies for the many components of curtain walls are organized in racks. (*b*) A heated billet of aluminum is inserted into the cylinder of the extrusion press. (*c*) An extrusion emerges from the die. (*d*) Long aluminum extrusions cool on rollers, ready for straightening and cutting to length. *(Courtesy of Kawneer Company, Inc.)*



(A) SHEAR BLOCK



(B) SCREW SLOT



(C) SNAP-TOGETHER FEATURES

FIGURE 21.4
Extrusion fastening. (*A*) A shear block is used to support a connection between two extruded members meeting at right angles. The shear block is an extrusion as well—a short piece cut from a longer length. Screw ports, as shown here, are an easy-to-extrude profile that allows for fastening parallel to the direction in which the piece was extruded. (*B*) Where screws are to be driven perpendicular to the extrusion, screw slots are used. In this example, screws pass through holes in an aluminum pressure plate and engage with matching threads machined into the screw slot. The pressure plate compresses the synthetic rubber gaskets, causing a tight seal with the glass. (*C*) Snap-together features are frequently used in extruded aluminum window and curtain wall components. Assembly is accomplished by aligning the components and tapping firmly with a rubber mallet or squeezing with a rubber-cushioned clamp.

Thermal Breaks

Compared to other common architectural metals, aluminum conducts heat rapidly (Figure 21.5). In very cold weather, the indoor surfaces of an aluminum member that passes from the outside of the building to the inside, such as a window frame, can become cold enough that moisture and even frost may condense on them. This is why all but the simplest aluminum framing systems are manufactured with *thermal breaks*, which are internal components of insulating material that isolate the aluminum on the interior side from that on the exterior side. Thermal breaks reduce the flow of heat through the member and improve the thermal performance of the complete assembly.

Figure 21.6 shows a *pour and debridge thermal break*, in which molten plastic is poured into a channel, called a barrier channel, in the center of an aluminum member, where it hardens. Then the aluminum that forms the bottom of the channel is cut away, leaving only the plastic to connect the two metal halves. In Figure 21.7, thermal breaks are created with preformed polyamide thermal strips that are mechanically inserted into the aluminum extrusions during their manufacture. The hollow space between the strips is filled with insulation material. *Polyamide strip thermal breaks* are more thermally efficient than pour and debridge breaks. Other thermal breaks rely on slotted aluminum members that reduce the cross-sectional area of metal connecting inside to outside, plastic clips or gaskets that isolate exterior covers from the internal parts of framing systems, and even double pour and debridge breaks, in which two such breaks are arranged in line, creating a greater resistance to heat flow.

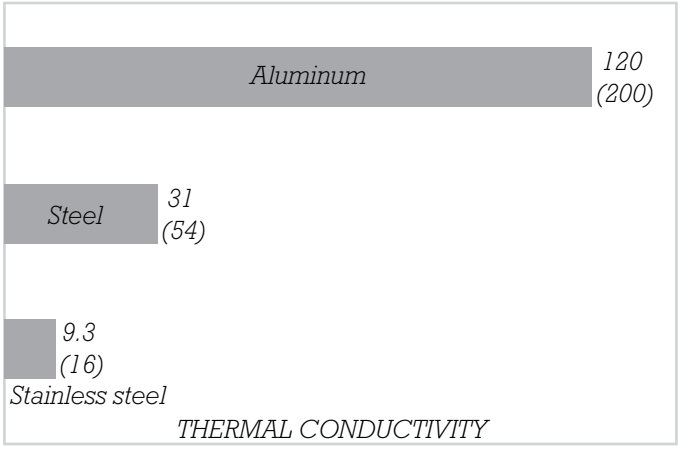
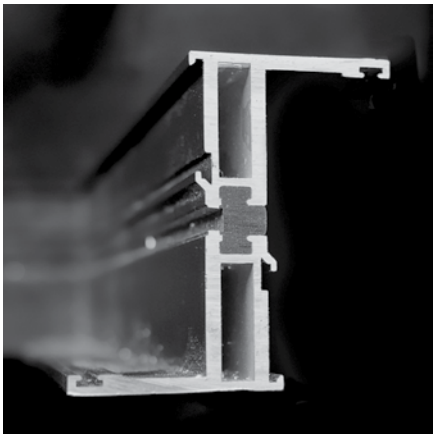


FIGURE 21.5
Thermal conductance of aluminum, ordinary carbon steel, and stainless steel. Aluminum conducts heat roughly 4 times faster than carbon steel and 12 times faster than stainless steel. Units are Btu/hr-°F-ft and (W/m-K).



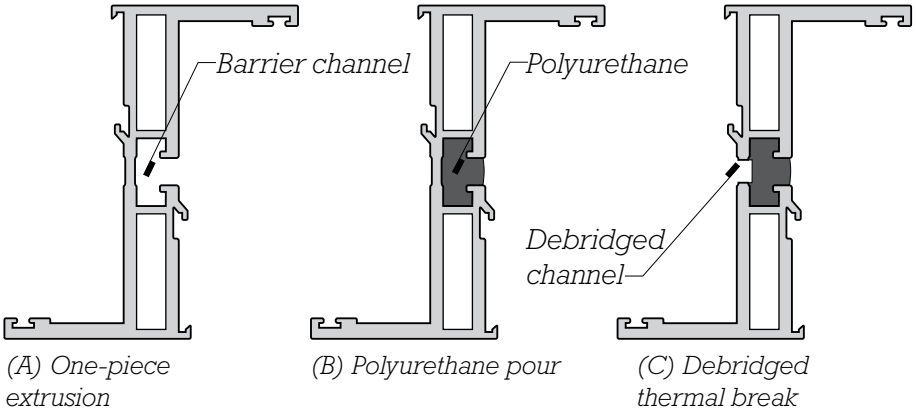


FIGURE 21.6
Steps in the manufacture of a pour and debridge thermal break. (*A*) Two halves of a window frame are extruded as a single piece. (*B*) Polyurethane plastic is poured into the barrier channel in the extrusion. (*C*) After the polyurethane has hardened, the center of the channel is cut away, or "debridged," leaving the two halves of the frame connected only by the hardened plastic.

Sustainability and Cladding with Metal and Glass

Energy Performance

By controlling the flow of heat, air, light, and sound, curtain walls and other metal and glass wall systems have a large impact on a building's energy performance and the physical and psychological comfort of building occupants.

Building and Material Life-Cycle Impacts

- Aluminum is easily recycled, and making aluminum from recycled metal requires as little as 5 percent of the energy required for its production from ore. Because of these efficiencies, in North America approximately 95 percent of construction aluminum scrap is recycled.
- The embodied energy of virgin extruded aluminum is approximately 140 MJ/kg (60,000 BTU/lb) and of recycled extruded aluminum, 34 MJ/kg (15,000 BTU/lb).
- A curtain wall manufacturer EPD reports the following cradle-to-gate impacts per square meter (11 sq ft) of glazed curtain wall:

Nonrenewable primary energy consumption	2500 MJ (2.3 million BTU)
Global warming potential	180 kg (390 lb) CO_2 eq.
Fresh water consumption	1100 L (290 gal)

Material and Production Attributes

- In North America, the postconsumer content of manufactured aluminum products is high, averaging around 60 percent.

Unhealthful Materials and Emissions

- Aluminum is generally free of recognized hazardous compounds.
- Aluminum does not emit VOCs. Many joint sealants used in the assembly of aluminum components and for the adhering of glass to framing have significant VOC emissions.

Responsible Industry Practices and Social Impacts

- The largest bauxite deposits are located in Guinea, Australia, Brazil, and Jamaica. Annually, approximately 50 square kilometers (20 square miles) of land are cleared of vegetation and topsoil, and mined to extract ore for the production of new aluminum. The aluminum industry claims that the current rate of ecological rehabilitation of spent mined areas equals the rate of land clearing for new mining.
- Large volumes of water are required for smelting and only a portion can be recycled and reused. Wastewater from aluminum manufacture contains cyanide, antimony, nickel, fluorides, and other pollutants.
- At current rates of production, there are economically available bauxite reserves for approximately another 300 years.
- Bauxite mining typically takes place in remote areas, where relatively small but vulnerable populations are located. The aluminum industry claims it is making vigorous efforts to perform its operations in a socially responsible manner.

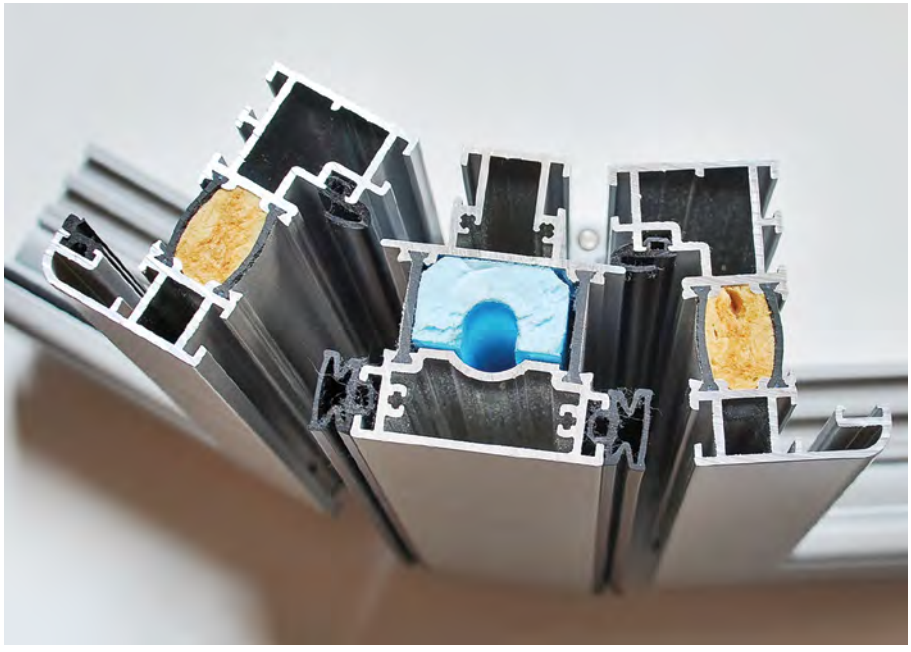


Figure 21.7
Polyamide strip thermal breaks. The extruded plastic strips are locked into preformed slots in the aluminum extrusions. The space between the thermal break strips is filled with plastic foam or mineral-fiber insulation. *(Photo by Joseph Iano.)*

Surface Finishes for Aluminum

Aluminum, though it is a very active metal chemically, does not corrode away in service because it protects itself with a thin, tenacious oxide film that seals the surface of the metal and discourages further oxidation. Although this film does an adequate job of protecting the aluminum, in the outdoor environment it develops a chalky or spotty appearance that can come to look rather shabby over time.

Anodizing is a manufacturing process that produces an integral oxide coating on aluminum that is thousands of times thicker and more durable than the natural oxide film that would otherwise form. The component to be anodized is immersed in an acid bath and becomes the anode in an electrolytic process that takes oxygen from the acid and combines it with the aluminum. Color can be added to the coating by means of dyes, pigments, or special electrolytes. The colors most frequently used in buildings are the natural aluminum color, golds, bronzes, and black, but other colors are possible. The advantages of anodized finishes are their extreme hardness and, in most colors, their excellent resistance to weather and fading.

Aluminum cladding components can also be finished with a variety of organic coatings. *Fluoropolymer coatings* are based on highly inert synthetic resins, such as *polyvinylidene fluoride* (*PVDF*) and *fluoroethylene vinyl ether* (*FEVE*), which are exceptionally colorfast and resistant to all forms of weathering, including ultraviolet deterioration. The PVDF finishing process begins with chemical cleaning of the metal. In a two-coat finish, a primer coat and PVDF finish coat are then each spray-applied. In a three-coat finish, a PVDF clear coat or special-effects coat is added to enhance appearance and provide additional protection. After the application of each of the PVDF coats, the aluminum piece is passed through an oven and baked at approximately 500 degrees Fahrenheit (250°C), a process that causes the resin molecules to intertwine and fuse into a tightly bonded matrix. FEVE finishes are also applied in two- or three-coat systems. However, unlike PVDF, FEVE can be applied either at elevated or ambient temperatures, making it also suitable for application in the field. Fluoropolymer coatings are available in a broad spectrum of colors, including bright metallic finishes. They are the most expensive of the organic coatings and the longest lasting; the best of them can be expected to last 20 years or more under normal service conditions.

Powder coatings are manufactured with thermosetting powders that are composed of plastic resins, such as polyester, and pigments. The powder is electrically charged and then sprayed onto the aluminum component, which is grounded so that the powder adheres to it electrostatically. The component is then passed through an oven, where the powder fuses to produce a hard, resistant coating, usually in a single application. Among the advantages of powder coatings are their lower cost in comparison to fluoropolymers, their durability, the wide range of colors and finishes in which they are available, and their freedom from organic solvents that cause air pollution. More recently, both PVDF and FEVE have become available as powder coat resins, making it possible to combine the high performance of these polymers with the efficiencies of the powder coating process.

Baked enamel coatings, consisting of spray-applied acrylic or polyester polymers (which are sometimes modified with silicone), are also used as aluminum coatings. They are inexpensive and provide finishes with very high glosses in a wide selection of colors.

A wide range of surface effects may be applied to aluminum by mechanical and chemical processes. Mechanical finishes are produced by such means as wire brushing, wheel or belt polishing, buffing, grinding, burnishing, barrel tumbling, sandblasting, blasting with steel shot or glass beads, and abrasive blasting. Each produces a different surface texture. Chemical finishes include bright dipping, which produces mirror-like surfaces; etching; and chemical conversion coatings, such as oxides, phosphates, and chromates. Mechanical and chemical finishes may be done in preparation for the application of other types of finishes, or in some cases may act as final finishes.

Other Curtain Wall Frame Metals

Although the vast majority of contemporary curtain wall framing is made from aluminum extrusions, other metals, such as bronze, galvanized steel, and stainless steel, may also be used. In comparison to aluminum curtain wall framing, steel allows for thinner sight lines and lower thermal conductivity.

FIGURE 21.8

Storefront, curtain wall, and window wall. Storefront framing bears directly on the floor structure beneath it and is braced laterally at its top by the structure above. It is used at ground floors, or occasionally for several floors above grade. Curtain wall is hung off the edges of the floor slabs, spans multiple floors, and can be used on buildings of any height. Window wall, like storefront, bears on the slab below and is braced by the structure above. But, like curtain wall, it can be used on tall buildings.

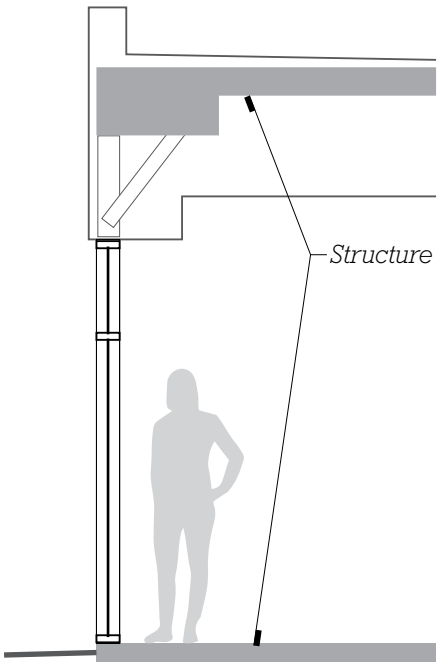
Aluminum and Glass Framing Systems

Aluminum and glass framing systems used for the enclosure of large wall areas come in three types: storefront, curtain wall, and window wall (Figures 21.8 and 21.9).

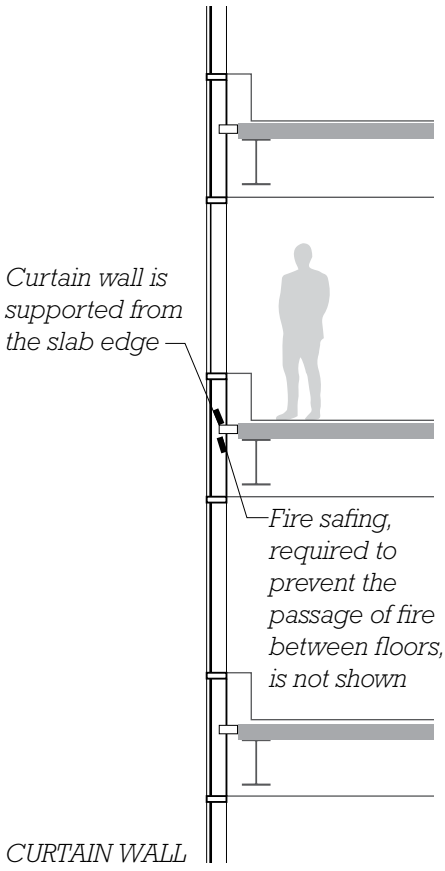
Storefront is the simplest and least costly of the three. It is constructed of relatively lightweight aluminum extrusions that are easily assembled and glazed in the field. The framing members range in size from 1½ to 2 inches (44 to 50 mm) in width and 4½ to 6 inches (100 to 150 mm) in depth, and can span vertically up to 10 to 12 feet (3.0 to 3.7 m). Because of its lightweight members and simple design, storefront is only suitable where wind and rain exposures are relatively mild. For this reason it is used at ground floors or, occasionally, no more than one to two stories above grade.

Curtain wall is used where the vertical spans between floors or the severity of exposure to wind and rain exceed storefront limitations. Its aluminum extrusions are heavier, stronger, and stiffer than those used in storefront. It employs more complex internal construction that is better able to resist water penetration even at high wind pressures. And its method of attachment to the building is different. Unlike storefront, which rests on the building structure and spans only between floors, curtain wall is hung off the side of the structure and can span many floors. As discussed in further detail later in this chapter, curtain wall systems can be assembled in the field or delivered to the construction site as prefabricated units. On the world's tallest buildings, custom curtain wall systems, individually designed and tested to meet the unique requirements of each building, are the enclosure systems of first choice.

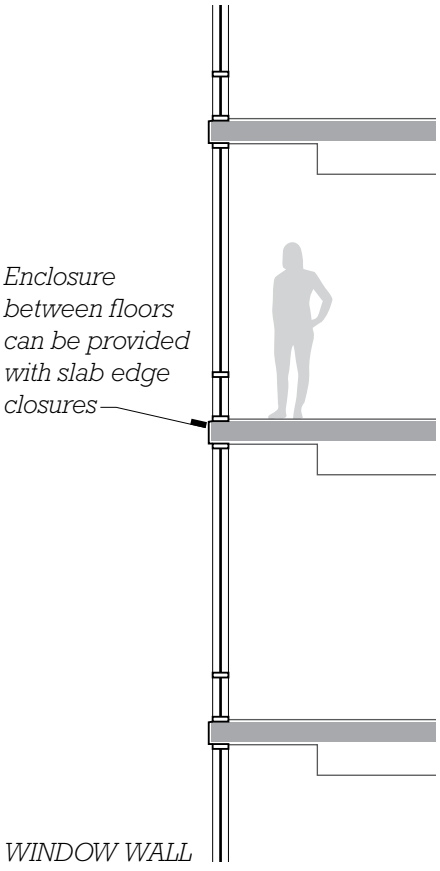
Window wall combines characteristics of both storefront and curtain wall. Like storefront, window wall framing bears directly on the supporting structure and spans only between single floors. However, like curtain wall, this system can be designed to resist water penetration at high wind pressures, making it suitable for use on tall buildings. Window wall can incorporate many types of aluminum framing and window types, as well as solid cladding materials. It allows most installation work to be performed from the interior side of the wall and is frequently produced as prefabricated, preglazed units, ensuring consistent quality and reducing to a minimum complex joining and sealing in the field. With the addition of optional *slab edge closures*, a complete enclosure system spanning many floors can be provided.



STOREFRONT



CURTAIN WALL



WINDOW WALL

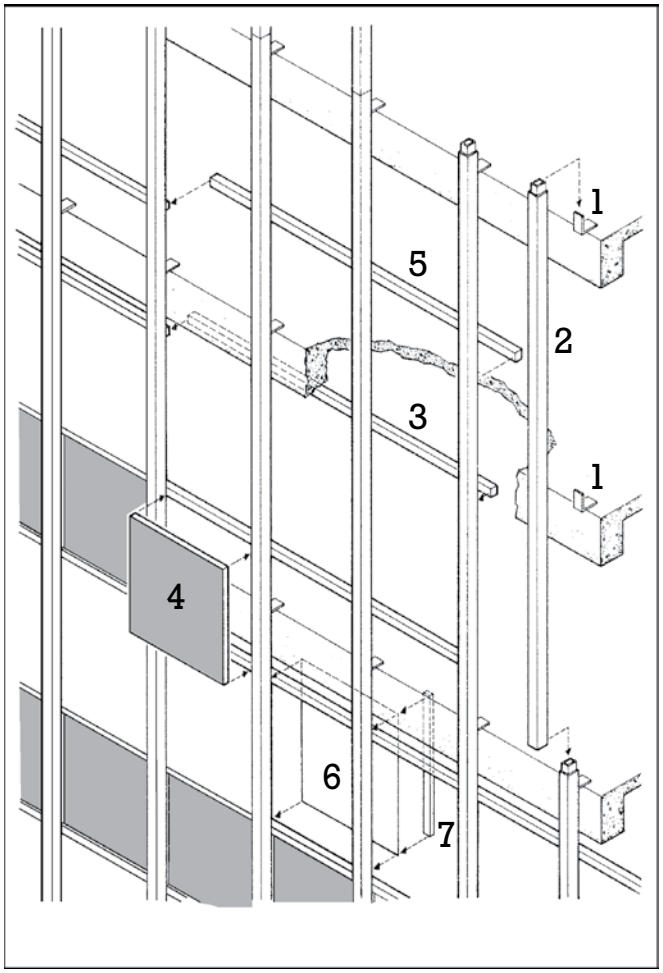
FIGURE 21.9
(*Top left*) Curtain wall can be adapted to buildings of virtually any shape and height. (*Top right*) Storefront is used mainly for ground level enclosures. (*Bottom*) Window wall can take many forms. Here, it mimics the appearance of traditional curtain wall. Also visible in this photograph are external shading devices. On this west-facing facade, these shades protect the building interior from glare and overheating caused by the low afternoon sun. The band of darker glazing in the middle of the narrower facade is curtain wall. *(Photos by Joseph Iano.)*

Modes of Assembly

There are two principle modes of curtain wall assembly. *Stick systems* (Figure 21.10) are delivered to the site in parts and assembled in the field. The extruded aluminum framing members may be precut to length or provided in stock lengths and cut to fit as they are assembled. The glass, spandrel panels, and other parts are all also field-installed. Stick systems have the advantages of low shipping bulk and ready adjustability to site conditions. But they must be assembled piece by piece on site rather than in a factory with its ideal tooling and controlled environmental conditions.

The *unit* (or *unitized*) *system* of curtain wall installation takes full advantage of factory assembly. Sections of curtain wall, usually as wide as one glass unit and as tall as one floor, are preassembled and preglazed in the factory. These prefabricated units require more space and more protection from damage during shipping than stick system components, but labor on the construction site is minimized. Installation can be performed from the interior side of the wall, and typically only one site-installed seal, at the joint between each unit and the next, is required. Unitized systems are best suited to large buildings with regular curtain wall configurations that can take maximum advantage of repetitive manufactured units.

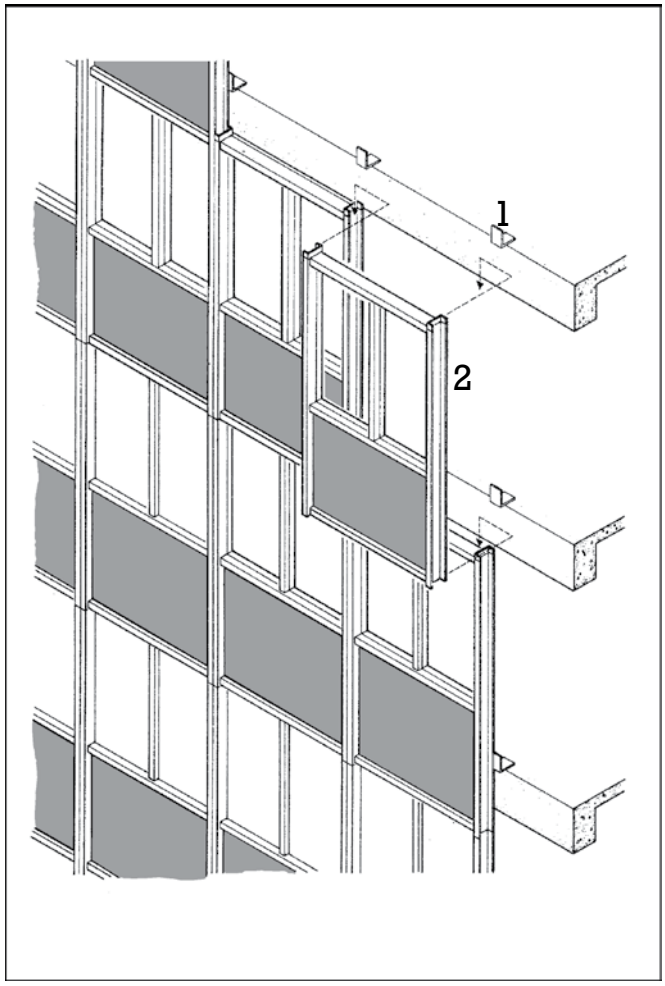
Storefront is always stick built, and window wall is usually prefabricated, very much like unitized curtain wall.



STICK SYSTEM– Schematic of typical version

1: Anchors. 2: Mullion. 3: Horizontal rail (gutter section at window head). 4: Spandrel panel (may be installed from inside building). 5: Horizontal rail (window sill section). 6: Vision glass (installed from inside building). 7: Interior mullion trim.

Other variations: Mullion and rail sections may be longer or shorter than shown. Vision glass may be set directly in recesses in framing members, may be set with applied stops, may be set in sub-frame, or may include operable sash.



UNIT SYSTEM– Schematic of typical version

1: Anchors. 2: Pre-assembled framed unit.

Other variations: Mullion sections may be interlocking "split" type or may be channel shapes with applied inside and outside joint covers. Units may be unglazed when installed or may be per-glazed. Spandrel panel may be either at top or bottom of unit.

FIGURE 21.10

Modes of assembly for curtain walls. *(Reprinted with permission from the AAMA's* Aluminum Curtain Wall Design Guide Manual.*)*

Water Management

Most aluminum and glass framing systems are designed as drained systems, with the expectation that water that leaks past exterior seals or condensation that occurs within the framing must be captured and drained back to the exterior. Figure 21.11 illustrates the water management strategy used with storefront systems. Water that penetrates past the exterior glazing seals collects in the glazing pockets. It then travels horizontally and vertically until it finds its way to the bottom of the framing, where it is collected in an extruded *subsill* and weeped to the exterior.

In curtain wall systems, water that penetrates the glazing seals flows toward, rather than out of, the horizontal mullions (Figure 21.12). At each such mullion, sealed plugs at the ends prevent water from draining downward while weeps in its face allow water to escape. Water is not drained to the bottom of curtain wall framing, as it is in storefronts, because the accumulated volume from many floors would overwhelm the system.

Figures 21.11 and 21.12 also illustrate how a continuous air barrier, an important part of all drained cladding systems, is maintained in these systems. Where curtain walls must resist water penetration at very high wind pressures, the glazing pockets are carefully compartmentalized and sealed, and fully pressure-equalized design is used. For more information about drained cladding systems,

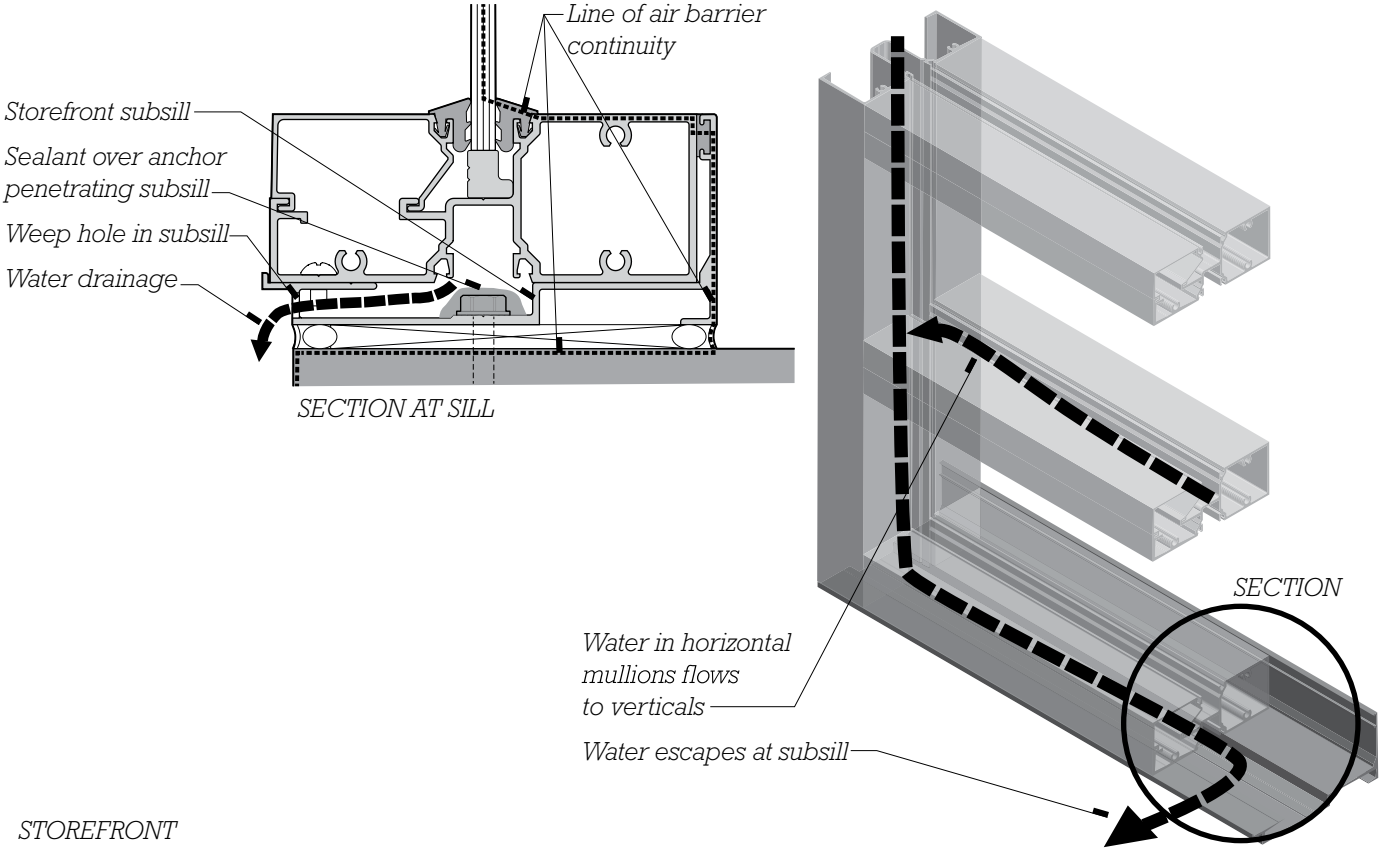


FIGURE 21.11

Water management in storefront glazing. Water falls to the bottom of the framing where it is captured by the subsill. The tall back leg of the subsill prevents water from leaking to the interior, while holes at the front allow the water to weep to the exterior. Except for the weep holes, the subsill must be completely watertight and is sealed with elastomeric sealant at potential leak points, such as fastener penetrations, extrusion joints, and at its ends.

air barriers, and pressure-equalized design, see Chapter 16.

Water management in window walls is similar to that in storefronts. Water that penetrates the outer seals is drained to the bottom of the framing at each floor, where it collects in a subsill and is weeped to the exterior.

Allowing for Movement

Aluminum framing and glass systems must account for differential movements between the glass, aluminum framing, and building structure. Movements between the glass and the aluminum may be caused, for example, by thermal expansions and contractions, deflections caused by wind pressures acting on the face of the glazing, or lateral displacements during a seismic event. These are accommodated by small flexing and sliding motions of the glass that occur within the glazing pockets and between the gaskets within which the glass is held. Rubber side blocks placed between the edge of the glass and the vertical mullions on either side prevent the glass from "walking" too far in either direction during repeated movement cycles.

Movements between aluminum framing and the building are caused mainly by thermal expansion and contraction of the aluminum, and deflections or long-term creep in the building structure. In the curtain wall system illustrated in this chapter, vertical movements in the aluminum framing are absorbed by telescoping

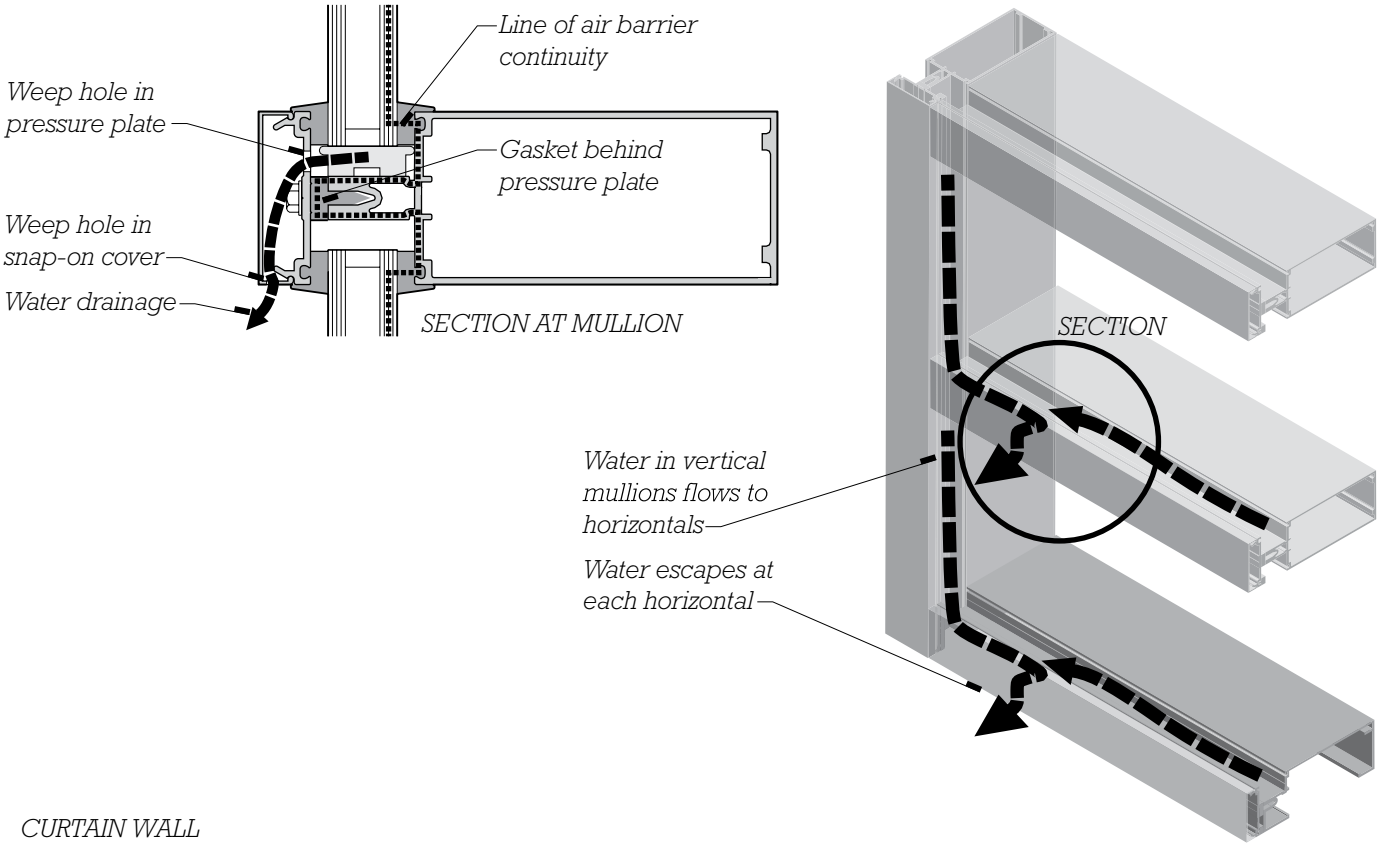


FIGURE 21.12

Water management in curtain wall glazing. Water within vertical mullions flows into the horizontal mullions. Each horizontal mullion provides weeps to the exterior through the concealed pressure plate and snap-on cover. The gasket behind the pressure plate serves as both a water seal and modest thermal break that reduces heat flow through the framing.

joints provided at regular intervals in the vertical mullions (Figure 21.13). Horizontal thermal movement is accommodated by intentionally cutting horizontal components slightly short by a calculated fraction of an inch at each vertical connection. Because the horizontal mullions are interrupted at each vertical, there are many of these joints to work together in absorbing expansions and contractions. Another example of a mullion connection that permits vertical movement is shown in Figure 21.17*b*.

Because storefront and window wall systems span the height of only one floor, vertical expansion and contraction within the framing is small and no special expansion provisions are required. However, where there may be significant vertical deflections in the supporting structure above, a *head receptor* (also called a *compensation channel*) may be added to allow unrestricted vertical movements while providing the necessary lateral support (Figure 21.14).

Outside and Inside Glazing

An *outside glazed* framing system requires that glass be installed or replaced by installers working from scaffolding or staging on the outside the building. An *inside glazed* system allows glass installation to be performed from the inside. Inside glazing is more convenient and more economical for a tall building, but it requires a somewhat more elaborate set of extrusions. Outside glazing systems utilize simpler, less expensive shapes but are usually reserved for buildings only up to approximately three stories in height. Storefront systems are always outside glazed. Curtain wall and window wall can be provided in both outside and inside glazed configurations. Some curtain wall systems are designed so that they can be glazed from either side.

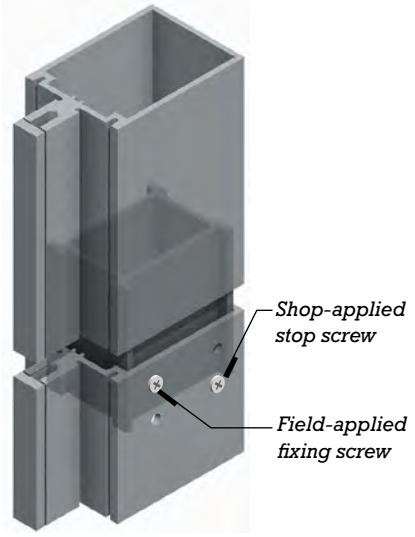


FIGURE 21.13
Sections of vertical mullion are spliced with an internal aluminum spline. The spline is screwed to the lower section of mullion, but the upper section is free to slide, which allows for movements between the two. *(Courtesy of Kawneer Company, Inc.)*

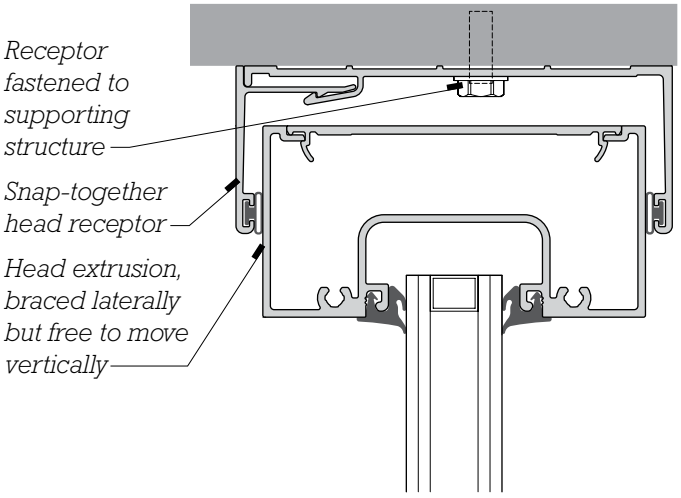


FIGURE 21.14
A head receptor permits vertical deflection in the supporting structure while providing lateral restraint to the framing system.

An Outside Glazed Curtain Wall System

The major parts of an externally glazed, stick system, aluminum-and-glass curtain wall are illustrated in Figure 21.15. As an outside glazed system, it is best suited to lower buildings, on which workers can reach the walls from external scaffolding, staging, or lifts. Vertical mullions run continuously from the bottom to the top of the curtain wall, while horizontals are made from shorter sections installed between verticals. As the pieces are assembled, silicone sealant is applied to many of the mating surfaces, ensuring continuous airtight and watertight boundaries within the system.

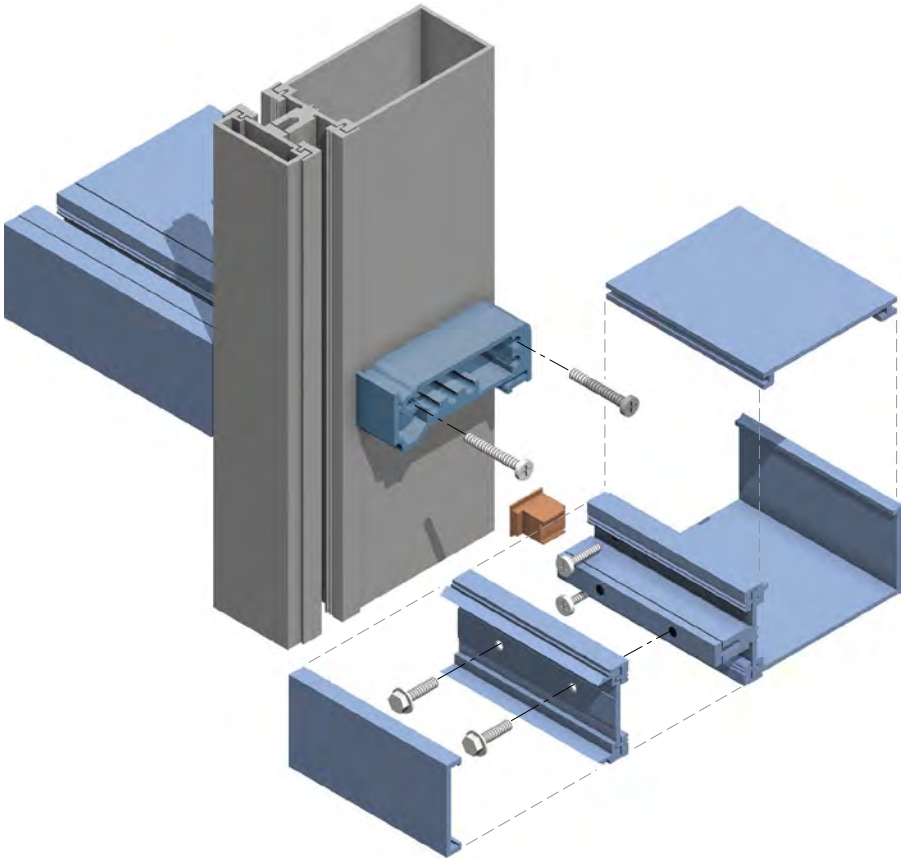


Figure 21.15
The Kawneer 1600 Wall System™ 1 is an outside glazed stick system. Connections between vertical and horizontal mullions rely on shear blocks and screws. Each lite of glass sits on two rubber setting blocks (not shown in this drawing) placed in the gutter of the horizontal mullion. The inner surface of the glass rests against rubber glazing gaskets pressed into small channels in the vertical and horizontal mullions. Extruded aluminum *pressure plates*, also with glazing gaskets, are applied to the outside of the mullions to clamp the glass into place. Each pressure plate is attached by means of screws that pass through drilled holes into an extruded, threaded screw slot. A thick rubber gasket in the screw slot acts as a thermal break and water seal. *Snap-on covers* conceal the screw heads and give a neat exterior appearance. A molded rubber *joint plug* (shown in the middle of the diagram) inserted at either end of each horizontal mullion contains leakage or condensate within the horizontal mullion, which escapes via small weep holes (not shown here) drilled through the pressure plate and the bottom edge of the snap-on cover. *(Courtesy of Kawneer Company, Inc.)*

Interactive Exercise

Figure 21.16 illustrates a common method of hanging vertical mullions from the edges of the building structure. A steel or aluminum angle attaches to either the edge of the floor slab or other perimeter structure, and to the side of the mullion. Slotted bolt holes allow for quick but precise alignment of the mullion during installation. Later, additional fasteners can be added or the connection can be welded, to prevent gradual slippage caused by cycles of thermal expansion and contraction or vibrations from fluctuating wind pressures. Figure 21.17 illustrates several steps in the installation of the same curtain wall system. And an example of a section going through a completed installation of such a system is shown in Figure 21.18.

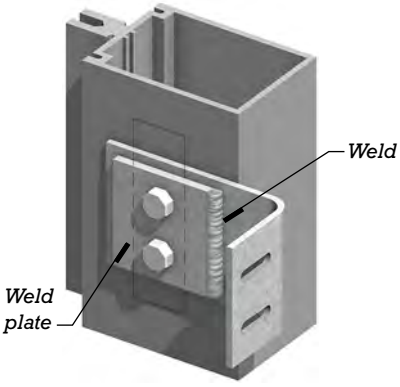
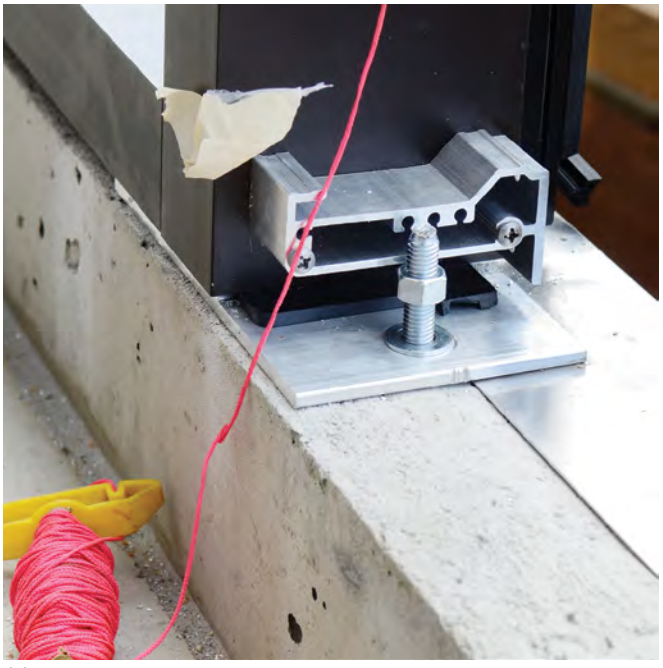


Figure 21.16
***Angle anchors*, with slotted bolt holes for easy adjustability during installation, are used to attach vertical mullions to the edges of the building structure.** *(Courtesy of Kawneer Company, Inc.)*

(*a*)

(*b*)



(*c*)

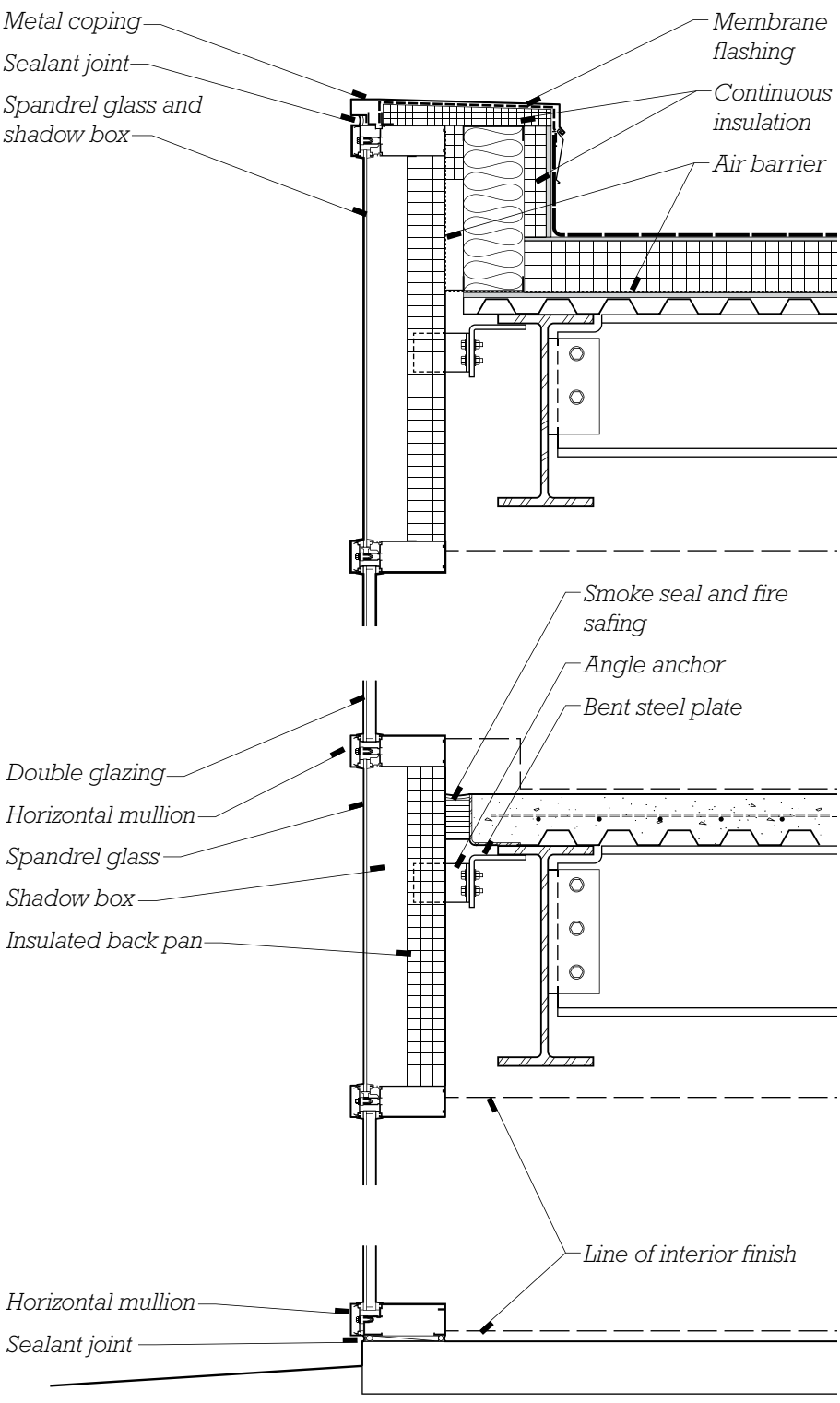
(*d*)

FIGURE 21.17

Assembly of a stick system curtain wall. (*a*) Installers use an articulated boom lift to access the work. Almost all of the work, including installation of glazing, will be performed from the exterior side of the wall. (*b*) A partially installed *wind load anchor.* Once this connection is completed, it will support the mullion laterally, without restraining vertical movement. Low-friction pads will be inserted between the sides of the U-shaped bent plate and the mullion. A bolt will be inserted through the anchor and holes yet to be drilled in the mullion. The bolt will be tightened only enough to secure the connection while leaving the mullion free to slide vertically. Beneath the anchor is a shear block. On the opposite side of the mullion, an installer uses a spatula to apply sealant at a horizontal mullion joint. (*c*) The base of a vertical mullion is fixed in place by an aluminum anchor plate bolted to the concrete foundation. The plate has two vertical legs that slip snugly inside the hollow mullion. This style of connector is called a *T-anchor:* the letter shape it roughly resembles turned upside down. After the anchor bolt is tightened, the protruding end of the bolt will be cut off to make room for the horizontal mullion that is yet to be installed. (*d*) A rubber joint plug seals the end of the horizontal mullion. Additional sealant will be applied as the joint is assembled to make the joint fully watertight. *(Photos by Joseph Iano.)*

FIGURE 21.18

In a finished installation, all the major enclosure functions must be maintained continuously between the curtain wall and other building components. At the top of the wall, membrane flashing completes the water control layer between the roof membrane and the curtain wall framing. In the same way, insulation within the parapet creates a continuous layer of thermal control. Air barrier continuity is maintained by extending the roofing system air barrier to the back of the curtain wall framing. Structural support for the curtain wall is provided by angle anchors similar to the one shown in Figure 21.16 at each floor and roof level. Here, the anchors are attached to bent steel plates that were welded to perimeter steel beams at the steel fabrication shop. At the roof and each floor level, translucent spandrel glass and a *shadow box* conceal the interior structure while maintaining a degree of visual transparency when viewed from the exterior. The shadow box consists of an air space behind the spandrel glass, an aluminum sheet metal back pan mounted within the curtain wall framing, rigid insulation, and an air- and vapor-tight facing at the back of the insulation. At each floor level a *smoke seal* and *fire safing* prevent the rapid spread of fire and smoke between floors in the event of a building fire. At the base of the curtain wall, a sealant joint at the shoulder of the mullion provides air barrier continuity and water control between the curtain wall and floor slab. While not illustrated here, continuity of enclosure functions must be maintained where the vertical sides of the curtain wall meet other building systems as well.



Double-Skin Facades

A *double-skin facade* is constructed of two glass cladding systems separated by an airspace that is often wide enough to allow service personnel to pass between them (Figure 12.19). Various configurations of glazing and treatment of the space between the two skins are possible. Most often, one of the two skins is double-glazed, while the other relies on single glass. The interstitial airspace may be completely isolated from the interior and passively ventilated to the exterior, acting as a simple buffer between exterior and interior conditions. Or this space may be interconnected with the building's internal systems, for example by serving as a return air plenum for the HVAC system. Shading devices, such as louvered blinds or roller shades, are frequently integrated into the interstitial space, where they can capture solar heat gains before these gains reach the building interior. And by moderating exterior air pressures, double-skin facades can enable operable openings in buildings taller than would otherwise be practical. Where the interstitial space must be accessed for maintenance and glass cleaning, a minimum clear width of approximately 36 inches (900 mm) is required. Where access is provided by interior operable units, this space can be as narrow as 6 to 10 inches (150 to 250 mm).

Double-skin facades can reduce unwanted heat losses and gains through the wall, increase daylighting potential, provide a protected space for shading elements, permit natural ventilation designs in tall buildings, and create a quieter building interior than is possible with conventional glazing systems. However, they also subtract from usable floor area within the building. Though the second skin of the facade may be constructed of less expensive framing and glass than the first skin, this still constitutes an increase in construction cost. And, over the life of the building, twice as much glass surface must be cleaned on a regular basis.

Double-skin facade systems are most appropriate for glass walls that must meet stringent energy conservation targets, where the higher cost of construction can be amortized over a long time period in which it can be offset by increased energy savings, and where the creation of a high-performance building is an implicit goal of the building program.

Figure 21.19
The Lightcatcher building at the Whatcom Museum, by Olson Kundig, is clad with a double-skin facade. It acts as thermal buffer between the interior and exterior, relying on natural convection to ventilate the interstitial space. The choice of glass types allows filtered, diffuse light to reach the building interior. Operable window units within the wall are part of a system of natural ventilation for the building interior.
(Photo by Joseph Iano.)

Sloped Glazing Systems

When a metal and glass cladding system is tilted so that it is no longer vertical, it is called *sloped glazing*. While the basic approach to combining framing members and glass units remains the same, there are particular problems with respect to potential water leakage. When a surface is not vertical, it becomes impossible to always neutralize the force of gravity. And moisture that condenses on the interior surfaces of sloped glass can accumulate and drip onto occupants below. For these reasons, sloped glazing systems are designed to include internal drainage systems that collect water resulting from leakage or condensation and carry it to the outdoors.

For glass systems sloped more than 15 degrees from vertical, building codes restrict the types of glass used, to protect occupants below from the risk of injury from falling broken glass. The only glazing materials permitted without any limitations are laminated glass and plastic. Other glass types are permitted, subject to restrictions relating to the height of the glass above the floor, size of the lites, type of occupancy, and other factors. Alternatively, any glass type is permitted if a metal screen is installed below the glass that can catch shards should the glass break.

The Curtain Wall Design Process

For projects modest in size and relatively uncomplicated in design, a curtain wall is usually chosen from a manufacturer's available standard systems. In this case, responsibility for selection and installation of the components and performance of the completed system rests primarily with the manufacturer and installer. The design team's structural engineer accounts for loads imposed on the building structure by the curtain wall at its points of attachment. These include the weight of the curtain wall itself, along with wind and seismic forces that act on the wall. The architect addresses the interfaces between the curtain wall and the surrounding building elements, to ensure that enclosure systems and exterior and interior finishes are fully integrated. And in consultation with a building energy or mechanical systems consultant, requirements for the curtain wall glazing are defined and suitable glass types are selected.

For larger buildings or for cladding systems with unique requirements, the curtain wall may be custom-designed. In this case, a cladding consultant with specialized knowledge is usually added to the design team, to assist in the preparation of a preliminary design and performance requirements. This information is provided to one or more curtain wall manufacturers, who then submit proposals for further development of the system. As the design of the chosen system continues, prototypes may undergo preconstruction testing to validate the design and detect potential flaws. For truly unique designs, this testing takes place in specialized labs, performed on full-scale assemblies that may be as large as two stories in height and three or more bays in width. These tests determine the system's ability to resist wind loads, air infiltration, and water penetration, while tolerating thermal cycling, movements of the supporting frame, lateral displacements due to seismic events, and more.

During the construction phase, many curtain walls—both standard and custom—are tested again in the field. A common test is ASTM E1105, in which resistance to water penetration is tested by subjecting selected areas of the wall to a controlled air pressure difference between inside and outside while being uniformly wetted across their exterior surface. Field tests such as this are especially helpful in identifying flaws in the assembly and installation of the system early in the construction phase while there is still time to take corrective steps.

Metal Panel Cladding

Architectural sheet metal cladding is made of thin metal sheets, applied to walls in very much the same way as when this type of metal is used for roofing. Because the metal is relatively thin, it requires closely spaced seams and attachments to prevent waviness, or *oil canning*, in the sheets. This makes the choice of seam type and arrangement of seams figure prominently in the finished expression of the cladding (Figure 21.20). Metal sheets used for this type of cladding commonly range in thickness from 0.025 to 0.050 inch (0.64 to 1.27 mm), or nominally between

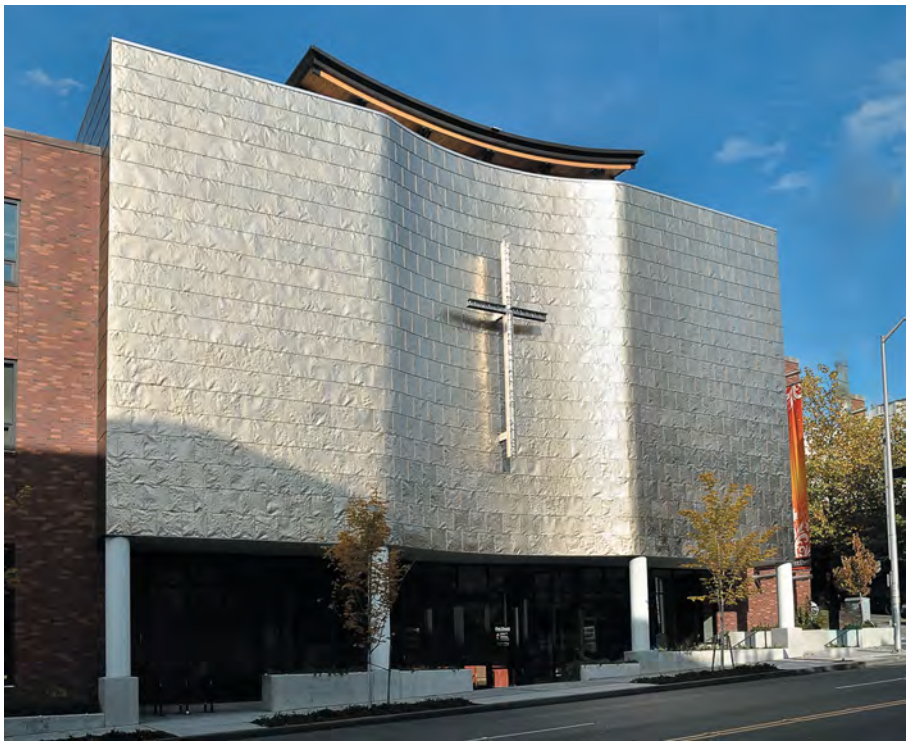


Figure 21.20
The main facade of the First Methodist Church in Seattle (Basetti Architects) is clad with titanium sheet metal, purposefully "crinkled" to create a textured surface with many specular highlights. *(Photo by Joseph Iano.)*

24 and 18 gauge. They are held in place with concealed sheet metal clips folded into the seams of the panels. For more information about architectural sheet metal materials, metal thicknesses, and attachment, see "Architectural Sheet Metal Roofing" in Chapter 17.

Thin sheets of metal can also be factory-formed into various ribbed or corrugated shapes called *formed metal wall panels*. These may be attached with exposed fasteners and resilient washers that deter water leakage at the penetrations through the panels or with a system of overlapping flanges and concealed fasteners. The profile of corrugation or ribs is the dominant feature of this panel type (Figure 21.21). Because the corrugations or ribs stiffen the sheets, larger panel sizes are possible and thinner sheets may be used in comparison to architectural sheet metal cladding.

Metal plate wall panels are made from heavier metal sheets, in the range of ⅛ to 3⁄16 inch (3 to 5 mm) thick. With proper attention to allowing for thermal expansion and contraction, these stiffer panels are capable of producing consistently flat or smoothly curved exterior surfaces with precise, uniform edges (Figure 21.22). Seams can be spaced at greater distances than with thinner sheet metal cladding. And rather than overlapping, or "shingling," the edges of adjacent sheets, panel edges may be kept flush, with a uniform gap in between. Many configurations of furring or anchorage are used to secure panels of this type to the backup structure (Figure 21.23).

Metal composite material (*MCM*) panels are similar in thickness and methods of attachment to metal plate panels but are made from thin sheet metal bonded to both sides of a thermoset plastic core. Though lower in cost than solid metal panels, the detailing and architectural expression are similar. The most common metal used for the facings is aluminum, in which case the panels may also be referred to as *aluminum composite material*, or *ACM*. Other available facing metals include zinc, copper, stainless steel, and titanium. Because the plastic core of the panel is flammable, North American building codes restrict the use of metal composite material panels on taller buildings unless the core is treated with chemical fire retardants or the panel application is limited in size and extent. Metal composite material panels may also be made

FIGURE 21.21
Variations in profile, orientation, and hue of formed metal wall panels create a strong, industrial aesthetic. *(Photo by Joseph Iano.)*

FIGURE 21.22
Museum of Glass, Tacoma, Washington, by architect Arthur Erickson. The conical dome is clad with stainless steel metal plate panels. *(Photo by Joseph Iano.)*

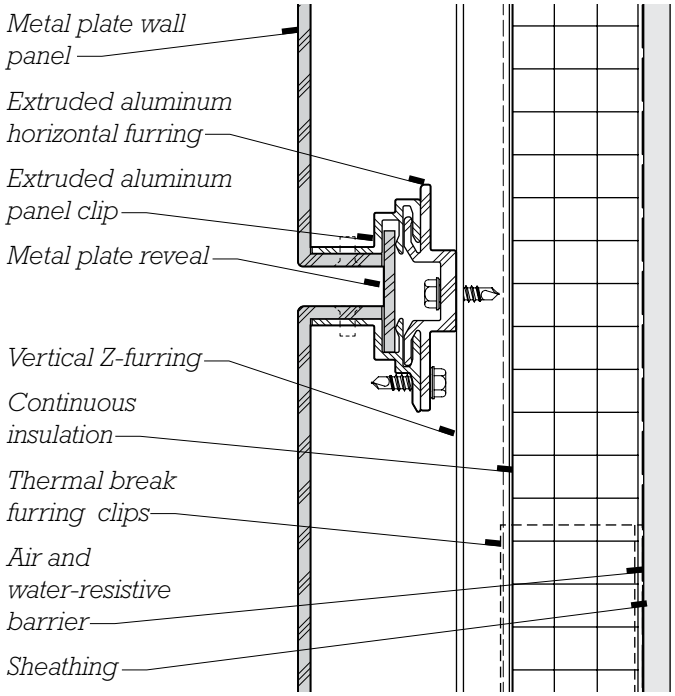


FIGURE 21.23
An extruded aluminum panel attachment system. The panels are mechanically fastened along their top and one of their side edges. The bottom edges and other sides are held in place by the interlocking extrusions. The furring system behind the panels consists of vertical, galvanized steel zees, attached to the wall with regularly spaced reinforced plastic thermal break clips.

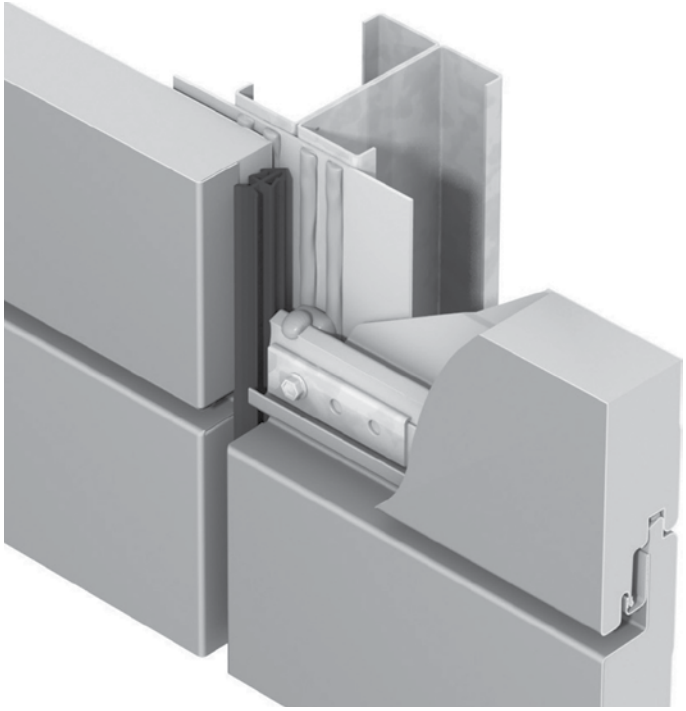


FIGURE 21.24
CENTRIA Formawall® aluminum-faced insulating metal panels, supported by light gauge steel framing members. Panels are mechanically fastened to the framing at their top corners. The bottom edge of the panel is held in place by its interlocking joint with the panel below. Solid gaskets between panels and sealant between panels and backing complete the air and watertightness of the assembly. *(Courtesy of CENTRIA. Formawall® is registered trademark of CENTRIA.)*

with cores fashioned from metal foil honeycomb or corrugated plastic to make panels up to 1 to 2 inches (25 to 50 mm) in thickness.

Insulated metal panels consist of sheet metal laminated to both sides of a rigid foam plastic insulating core. When fabricated with a complete system of interlocking edge seams, these lightweight, easy-to-erect panels can provide many of the separate enclosure functions of the exterior wall in one factory-made component, including control of the passage of heat, exterior water, air, and water vapor. Panels can be designed as a barrier wall system or, with the addition of an airspace and airtight drainage plane behind the panels, as a drained cladding or rainscreen system (Figure 21.24).

MasterFormat Sections for Cladding with Aluminum and Glass

07 42 00	**WALL PANELS**
07 42 13.13	Formed Metal Wall Panels
07 42 13.16	Metal Plate Wall Panels
07 42 13.19	Insulated Metal Wall Panels
07 42 13.23	Metal Composite Material Wall Panels
07 61 00	**SHEET METAL WALL CLADDING**
08 41 00	**ENTRANCES AND STOREFRONTS**
08 43 00	Storefronts
08 44 00	**CURTAIN WALL AND GLAZED ASSEMBLIES**
08 44 13	Glazed Aluminum Curtain Walls
08 44 33	Sloped Glazing Assemblies
08 46 00	**WINDOW WALL ASSEMBLIES**

Key Terms

bauxite
smelting
aluminum alloy
temper
extrusion
cast aluminum log
billet
die
shear block
screw slot
screw port
thermal break
pour and debridge thermal break
polyamide strip thermal break
anodizing
fluoropolymer coating
polyvinylidene fluoride, PVDF
fluoroethylene vinyl ether, FEVE
powder coating
baked enamel coating
storefront
curtain wall
window wall
slab edge closure
stick system
unit system, unitized system
subsill
head receptor, compensation channel
outside glazed
inside glazed
pressure plate
snap-on cover
joint plug
angle anchor
wind load anchor
T-anchor
shadow box
smoke seal
fire safing
double-skin facade
sloped glazing
architectural sheet metal cladding
oil canning
formed metal wall panel
metal plate wall panel
metal composite material panel, MCM panel
aluminum composite material panel, ACM panel
insulated metal panel

Review Questions

1. For what reasons is aluminum the metal most frequently used in metal-and-glass cladding systems?
2. What are the relative advantages and disadvantages of stick and unitized curtain wall systems?
3. Describe the characteristic attachment features of aluminum extrusions.
4. What are the most common finishes applied to aluminum curtain wall components? What are the advantages of each?
5. How would you choose between an inside glazed system and an outside glazed one?
6. How does the strategy for managing water leakage differ between storefront and curtain wall?
7. Explain the differences between aluminum-framed storefronts, curtain walls, and window walls. What is an appropriate application for each?
8. In what way is a sloped glazing system more difficult to make watertight than a wall cladding system? How is this reflected in the details of a slope glazing system?

Exercises

1. Make photocopies of full-scale details of the vertical and horizontal mullions of a metal curtain wall or window wall system from a manufacturer's catalog. Paste the details on a larger sheet of paper and add notes and arrows to explain every aspect of them: the features of the extrusions, the gaskets and sealants, the glazing materials and methods, drainage (and if weeps are not shown, where should they be?), insulation, thermal breaks, rainscreen features, and so on. From your examination of the details, list the order in which the components would be assembled. Is the system glazed from inside the building or outside? How can you tell?
2. Obtain construction drawings for a building that includes curtain wall or window wall. In the wall system details, trace the continuity of primary enclosure systems (including control of liquid water, air, heat, and water vapor) between the curtain wall or window wall and the enclosure systems that surround it.
3. Design a coffee table that is made up of aluminum extrusions and a glass top. Design and draw complete details of the extrusions and connections. Select a surface finish for the aluminum. What type of glass will you use?

Selected References

American Architectural Manufacturers Association. *Aluminum Curtain Wall Design Guide Manual*. Schaumburg, IL, 2005. This publication covers its topic in exemplary fashion with clear text and beautifully prepared illustrations. The same organization also publishes a series of more specialized publications on various aspects of metal-and-glass curtain walls:

rainscreen design, care and handling of aluminum components, design of wind loads and wind tunnel testing, fire safety, test methods, installation procedures, finishes, and so on.

Murray, Scott. *Contemporary Curtain Wall Architecture*. New York, Princeton Architectural Press, 2009.

A brief history of curtain wall and diverse range of case studies of contemporary curtain wall designs are presented.

Websites

Aluminum Extruders Council: www.aec.org

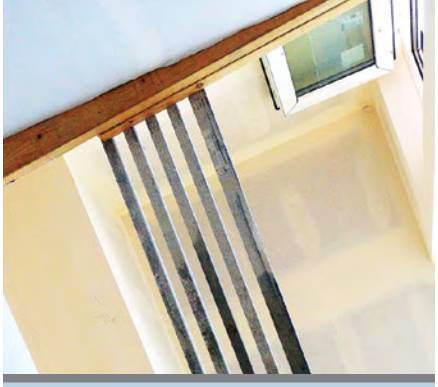
American Architectural Manufacturers Association: www.aamanet.org

CENTRIA (curtain wall): www.centria.com

EFCO (curtain wall): www.efcocorp.com

Kawneer (curtain wall and windows): www.kawneer.com

Whole Building Design Guide, Curtain Walls: www.wbdg.org/guides-specifications/building-envelope-design-guide/fenestration–systems/curtain-walls



22

Selecting Interior Finishes

- Installation of Mechanical and Electrical Services
- The Sequence of Interior Finishing Operations

Sustainability and Interior Finishes

- Selecting Interior Finishes
  - Appearance
  - Durability and Maintenance
  - Acoustic Criteria
  - Fire Criteria
  - Other Surface Flammability Criteria
  - Indoor Environmental Quality
  - Allowing for Movement
  - Relationship to Mechanical and Electrical Services
  - Changeability
- Long-Term Trends in Interior Finish Systems

Telescoping plank scaffolding (viewed from below) spans a floor opening whose walls have been finished with gypsum wallboard. Finishing compound smooths and conceals the joints and fasteners in the wallboard. Once the joint compound has dried and been lightly sanded, the wall surfaces are ready for painting. *(Design by Studio Ectypos. Photo by Joseph Iano.)*

The installation of interior finish materials—ceilings, walls, partitions, flooring, casework, finish carpentry, and so on—cannot proceed at full speed until the roof and exterior walls of a building are complete and mechanical and electrical services have been installed. The roof and walls are needed to shelter the moisture- and temperature-sensitive finish materials from the weather. The mechanical and electrical services are needed to further stabilize interior temperature and humidity. And as these systems will in most cases be covered by finish materials, the systems must precede the interior finishes for this reason as well. Finish materials themselves must be selected to meet a bewildering range of functional parameters: durability, acoustical performance, fire safety, indoor air quality, maintainability, changeability over time, and more. They must also look good, presenting a neat appearance and meeting the design goals of the interior spaces.

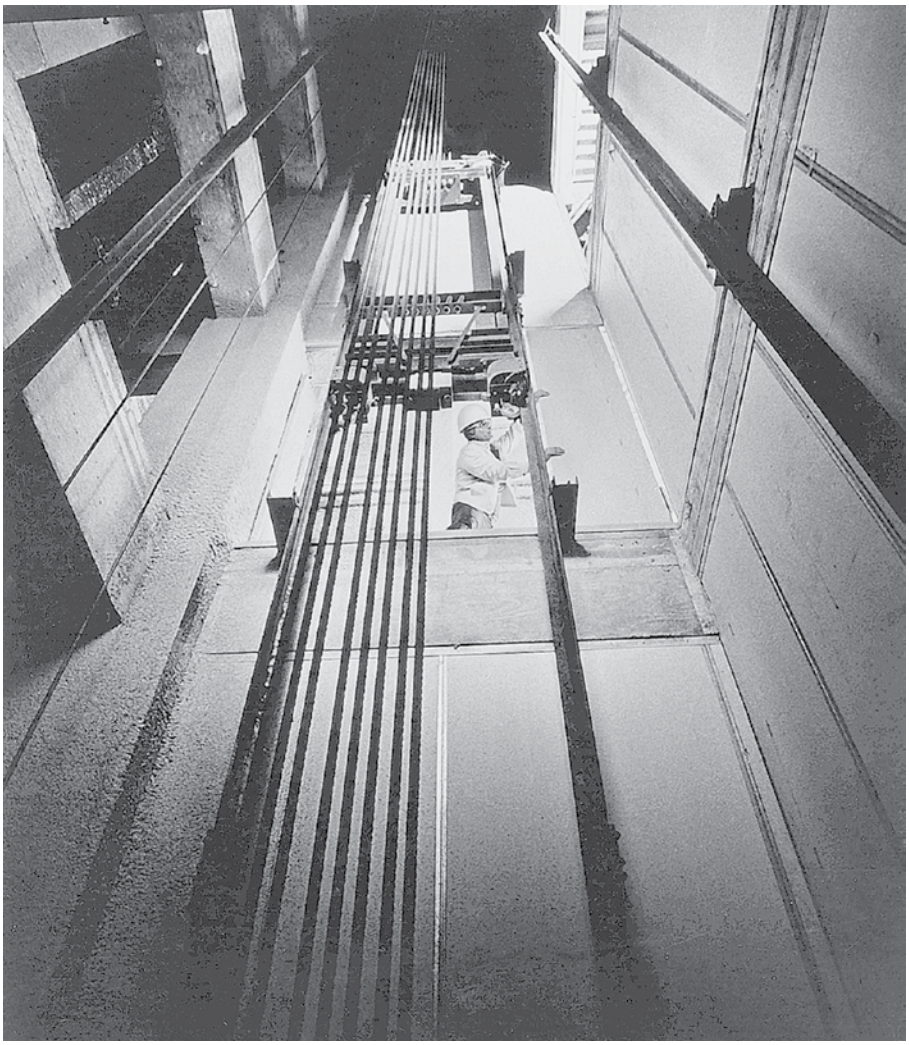


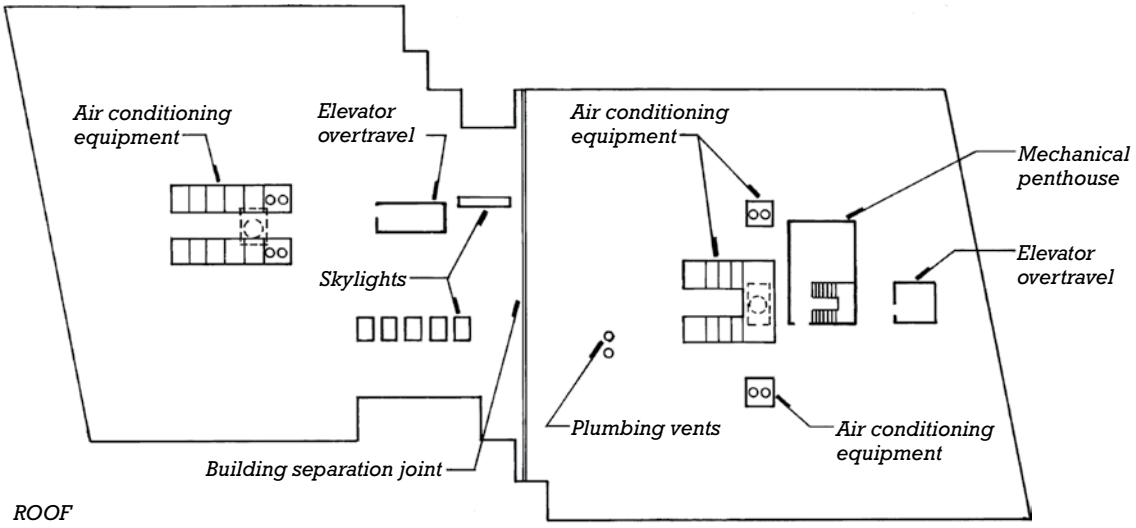
FIGURE 22.1
A worker constructs a fire-resistant wall around an elevator shaft using a gypsum shaft wall system. Chapter 23 contains more detailed information on shaft walls. *(Courtesy of United States Gypsum Company.)*

INSTALLATION OF MECHANICAL AND ELECTRICAL SERVICES

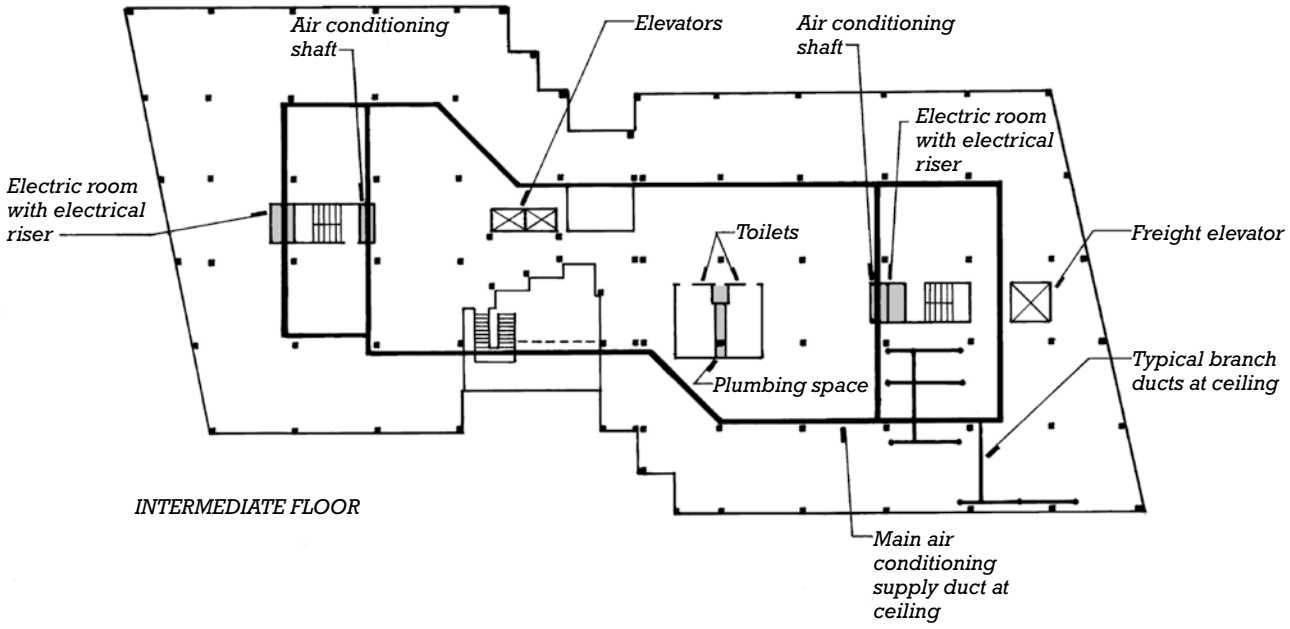
When a building has been roofed and its major wall enclosure components are in place, its interior is sufficiently protected from the weather that work can begin on mechanical and electrical systems. Plumbing waste lines are often the first system to be installed, as these are drained by gravity and have little flexibility in how they are routed. These are followed by potable water supply piping, and if needed, the pipes for a sprinkler fire suppression system. Next, the major part of the work for the *heating, ventilating, and air conditioning* (*HVAC*) system is carried out, including the installation of furnaces, boilers, chillers, cooling towers, pumps, fans, piping, and ductwork. The installation of electrical, communications, and control wiring follows, as do the installation of elevators and escalators in the structural openings provided for them.

The vertical runs of pipes, ducts, wires, and elevators through a multistory building are made through vertical *shafts* whose sizes and locations were determined at the time the building was designed. Before the building is finished, each shaft will be enclosed with fire-resistive walls to prevent the rapid vertical spread of fire (Figure 22.1).

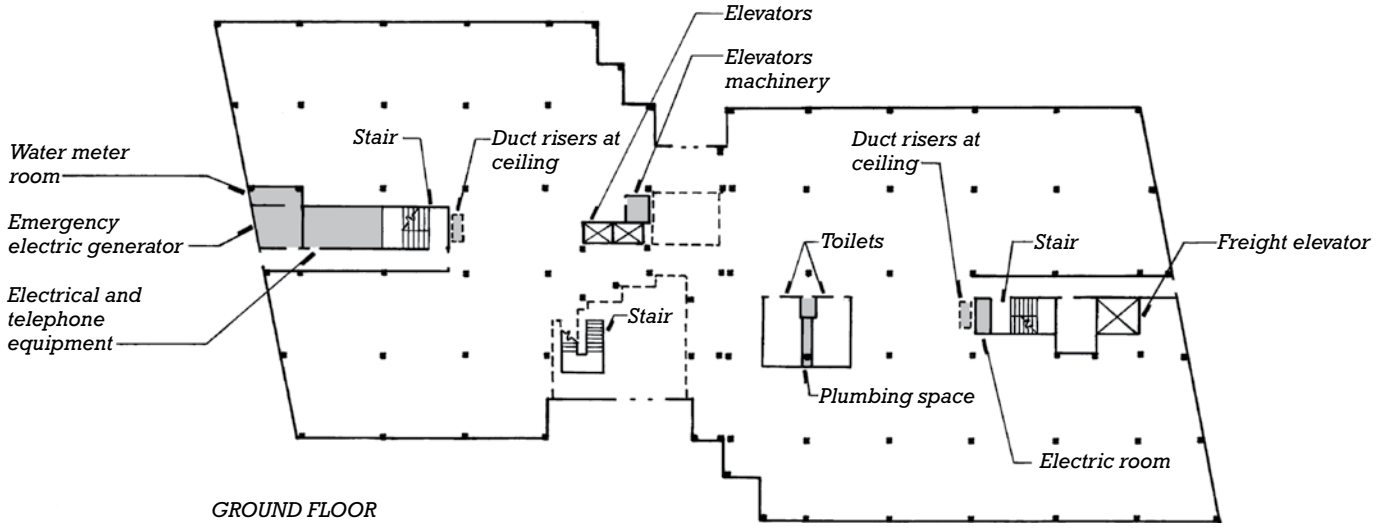
FIGURE 22.2
Three diagrammatic plans for a three-story suburban office building show the principal arrangements for plumbing, communications, electricity, heating, and cooling. Heating and cooling are accomplished by means of air ducted downward through two shafts from equipment mounted on the roof. The conditioned air from the vertical ducts is distributed around each floor by a system of horizontal ducts that run above a suspended ceiling, as shown on the plan of the intermediate floor. A row of doubled columns divides the building into two independent structures at the building separation joint to allow for differential foundation settlement and thermal expansion and contraction. *(Courtesy of ADD Inc., architect.)*



ROOF



INTERMEDIATE FLOOR



GROUND FLOOR

Sustainability and Interior Finishes

Interior finish materials are protected from the exterior elements. They are not subject to wind pressures; large, frequent changes in temperature; or the direct rays of the sun. And, except in limited areas, they are kept dry. With such benign conditions, the range of material and finish choices is greatly expanded. Interior finishes also share the same environment with building occupants. They engage all five senses. They significantly impact the visual and acoustic environments. And if these materials introduce harmful compounds into the interior environment, they can become sources of serious negative health effects. The designer's challenge is to select finishes that meet the functional and aesthetic goals of a project while minimizing environmental impacts and protecting the well-being of building occupants.

Building and Material Life-Cycle Impacts

- Finish materials can be formulated for recycling or repurposing, making it easier to divert these products from landfills at the end of their useful life.

Material and Production Attributes

- Finish materials made with high recycled content reduce the demand for virgin materials and the negative environmental impacts that come from extracting from the ground or harvesting such materials.
- Interior finishes derived from rapidly renewable sources, such as bamboo, straw, and agricultural byproducts, reduce the depletion of raw materials of limited supply.
- Finish materials that are extracted, processed, and manufactured locally require less energy to transport, and their use helps to support local economies.

Horizontal runs of pipes, ducts, and wires are usually located just underneath each floor slab, above the ceiling of the floor below, to keep them up out of the way. These may be left exposed in the finished building or, as is more common, hidden above suspended ceilings. Sometimes these services, especially wiring, are concealed within a hollow floor structure such as cellular metal decking or cellular raceways. Sometimes services are run between the structural floor deck and a raised access flooring system. (For a more complete explanation of these systems, see Chapter 24.) Where space is needed for supply and waste piping behind wall-mounted plumbing fixtures, double walls are constructed that readily accommodate these items.

Dedicated floor areas are reserved for mechanical and electrical functions in larger buildings (Figure 22.2). Distribution equipment for electrical power and communications wiring is housed in special rooms or closets. Fan rooms are often provided on each floor for air-handling machinery. In a large multistory building, space is set aside, usually at a basement or subbasement level, for pumps, boilers, chillers, electrical transformers, and other heavy equipment. At the roof are penthouses for elevator machinery and mechanical system cooling towers and ventilating fans. In very tall buildings, one or more whole floors may be set aside for mechanical equipment, and the building zoned vertically into groups of floors that can be reached by ducts and pipes that run up and down from each of these dedicated mechanical floors.

The Sequence of Interior Finishing Operations

Interior finishing operations also follow carefully ordered sequences. The first finish items to be installed are usually hanger wires for suspended ceilings, and full-height partitions and enclosures, especially those around mechanical and electrical shafts, elevator shafts, mechanical equipment rooms, and stairways. After the major horizontal air ducts and electrical conduits have been installed, the grid for the suspended ceiling is attached to the hanger wires so that the lights and ventilating louvers can be mounted. Then, the ceilings are finished and framing for the partitions that do not penetrate the finish ceiling is installed. Electrical and communications wiring is brought down from above the ceilings to serve outlets in the partitions. The walls are finished and painted. The last major finishing operation is the installation of the flooring materials. This is delayed as long as possible to let the other trades complete their work and get out of the building. Otherwise, the floor materials could be damaged by dropped tools,

- Selecting materials that are free from carcinogens, persistent bio-accumulative toxins, and other harmful chemicals can reduce the health risks to building occupants and others who come in contact with these materials during their manufacture, installation, and disposal.

Unhealthful Materials and Emissions

- Indoor finish materials and coatings present large surface areas to the interior environment of a building, making them potentially significant sources of emissions and indoor air quality problems.
- Materials that are wet-applied on the construction site, such as coatings, adhesives, and sealants, are potential sources of volatile organic compound (VOC) emissions. By limiting the VOC content of these materials, the health of the materials installers and eventual building occupants are better protected.
- Composite wood materials are a potential source of significant formaldehyde gas emissions. Materials manufactured without formaldehyde resins or with ultra-low-emitting resins can be selected to minimize building occupant exposure to this chemical and its health risks.
- As discussed further in the main text, emissions testing of insulation, wallboard, paints and coatings, flooring, ceiling systems, furniture, and other interior materials can ensure that only low-emitting products are selected.
- Some materials are inherently non-emitting and do not create potential air quality concerns. These include, for example, stone, ceramics, metals, glass, concrete, and clay masonry, as long as they do not include potentially emitting finishes, binders, or sealants.

Responsible Industry Practices

- Materials reclamation or recycling programs, run by materials manufacturers or by industry-supported consortiums, can increase rates of materials recycling and waste diversion.

spilled paint, heavy construction equipment, and construction debris ground underfoot.

Selecting Interior Finishes

Appearance

A major function of interior finish components is to make the interior of the building look neat and clean by covering the rougher and less organized portions of the framing, insulation, electrical wiring, ductwork, and piping. Beyond this, the architect designs the finishes to carry out a particular concept of interior space, light, color, pattern, and texture. The form and height of the ceiling, changes in floor level, interpenetrations of space from one floor to another, and the configurations of the partitions are primary factors in determining the character of the interior space. Light originates from windows and electric lighting fixtures and is propagated by successive reflections off the interior surfaces of the building. Lighter-colored materials raise interior levels of illumination; darker colors and heavier textures result in a darker interior. Patterns and textures of interior finish materials are important in bringing the building down to a scale of interest that can be appreciated readily by the human eye and hand. No two buildings have the same requirements: Deep carpets and rich, polished marbles in muted tones may be chosen to give an air of affluence to a corporate lobby, brightly colored surfaces to create a happy atmosphere in a day-care center, and slick plastic and highly reflective surfaces to provide a trendy ambience for the sale of designer clothing.

Durability and Maintenance

Expected levels of wear and tear must be considered in selecting finishes for a building. Highly durable finishes generally cost more than shorter-lived ones and are not always required. In a courthouse, a transportation terminal, a recreation building, or a retail store, traffic is intense, and long-wearing materials are essential. In a private office or an apartment, more economical finishes are usually adequate. Water resistance is an important attribute of finish materials in kitchens, bathrooms, locker and shower rooms, entrance lobbies, and some industrial buildings. In hospitals, medical offices, kitchens, and laboratories, finish surfaces must not trap dirt and must be easily cleaned and disinfected. Maintenance procedures and costs are also considered in selecting finishes: How often will each surface be cleaned, with what type of equipment, and how much will this procedure add to the cost of owning the building? How long will each surface last, and what will it cost to replace it?

Acoustic Criteria

In everyday architectural spaces, such as those used for work and living, acoustical performance relates mainly

to the control of noise levels, speech intelligibility within the space, and privacy between adjacent spaces. Interior finish materials strongly impact these criteria.

Sound

Sound intensity is expressed in *decibels* (*dB*), a measure of the amplitude of the air pressure waves by which it is carried. For example, the average human pain threshold for very loud sound is around 110 dB; sound levels in an open office environment are typically in the range of 40 to 60 dB; and a human whisper has an intensity of approximately 20 dB. The decibel scale is not linear. Instead, each 10 dB increase represents an approximate doubling of the perceived loudness. The decibel scale is also sometimes adjusted to more closely reflect human perception of sound, in that higher-pitched sounds are perceived as louder than others lower in pitch, even when the two are of equal measured intensity. The *dBA* scale is a decibel scale weighted to more accurately reflect this perception.

Sound pitch is measured in frequency, as cycles per second, or *Hertz* (*Hz*). The frequency range of audible sound is from roughly 20 Hz (low-pitched) to 20,000 Hz (high-pitched).

Sound can travel through the air, as a pressure wave, or through solid materials, as vibrations within the material. Examples of sources of *airborne sound* include human speech, sound emitted from loudspeakers, and a live music performance. *Structure-borne sound* travels as vibrations within the solid components of the building. Common sources include footfall on hard-surfaced floors and vibrations originating from motors in mechanical equipment attached to the building structure.

Sound Absorption

In noisy environments, interior surfaces that are highly absorptive of airborne sound can decrease noise intensity to more tolerable levels. The sound absorption of a wall or ceiling material is measured as its *Sound Absorption Average* (*SAA*) or *Noise Reduction Coefficient* (*NRC*). SAA and NRC are both numbers between 0 and 1 (or slightly greater than 1 due to peculiarities of the test method). Higher values indicate better sound absorption within the normal speech range. An SAA or NRC of 0.8 indicates that a material absorbs approximately 80 percent of the sound that reaches it and reflects the remaining 20 percent back into the space. Concrete has an SAA or NRC of very close to 0, while materials used to absorb sound typically have values of 0.5 or greater. By covering a larger frequency range in more finely divided increments, SAA provides a more precise measurement result than NRC.

In spaces with many hard, smooth finish surfaces, sound can sustain itself through repeated reflection off of these surfaces well after the source of the sound has stopped, an effect called *reverberation*. In some spaces (for example, music halls), extended reverberation times contribute positively to the acoustic character of the space. However, in everyday work and living spaces, excessive sound reflections impair speech legibility, and sound absorbing materials are frequently used in such spaces to also control reverberation times.

Partition Acoustic Isolation

Between rooms, acoustic privacy from airborne sounds can be provided by partitions that are both heavy and airtight. The acoustic isolation properties of lighter-weight partitions can be enhanced by additional layers of wallboard (to increase mass), resilient mountings on one of the partition surfaces (that dampen the transmission of structure-borne sound), and sound-absorbing *acoustic insulation* batts within the interior cavity of the partition. Manufacturers test full-scale partitions for their ability to reduce the passage of sound using a procedure described in ASTM E90. The results of this test are converted to *Sound Transmission Class* (*STC*) numbers that can be related to accepted standards of acoustic privacy.

STC numbers describe the decrease in intensity as sound travels from one side of a partition to the other. For example, with an STC 55 partition, an 80 dBA sound on one side will be reduced to 25 dBA on the opposite side. With an STC 25 partition, normal speech on one side is easily intelligible on other side. With an STC 50 partition, loud music can only be faintly heard on the opposite side. The International Building Code requires partitions between living or sleeping units and adjacent spaces to have STC ratings of at least 50. To achieve the acoustical performance credit in the LEED sustainability program, such elements must have an STC rating of at least 55.

In a completed building, the level of acoustic isolation that can be achieved between adjacent spaces is less than that predicted by laboratory testing. This is caused by *sound flanking*, that is, the presence of sound pathways that circumvent the partition construction due to gaps around the partition edges, openings in the wall surface for electrical power outlets and switches, lapses in construction quality, adjacent assemblies of different construction, etc. To determine the sound isolation in a constructed setting, *Field STC* (*FSTC*) or *Apparent STC* (*ASTC*) measurements are made according to a different standard, ASTM E336. These measurements typically range 5 to 10 points lower than those derived in the laboratory.

Floor-Ceiling Acoustic Isolation

When one interior space is located beneath another, the transmission of structure-borne sound through the floor-ceiling assembly (for example, from footfall on the floor above) is measured according to ASTM E492. In this laboratory test, a machine taps on the floor above while instruments in a chamber below record sound levels. The results are reported as *Impact Isolation Class* (*IIC*) ratings. IIC ratings relate to reductions in

sound intensity through the floor-ceiling in the same way as STC ratings relate to the reduction of sound intensity through partitions. And similar to FSTC ratings, *Field IIC* (*FIIC*) ratings can be determined for floor-ceiling assemblies with testing in completed buildings. Impact noise transmission can be reduced by avoiding hard flooring materials, with the use of soft or resilient underlayment boards or mattings beneath the flooring, or with resilient hangers or furring that decouple ceilings from the structure to which they are attached above. The International Building Code requires floor-ceilings above living or sleeping units to have IIC ratings of at least 50.

For additional acoustical criteria for ceiling systems, see Chapter 24.

Fire Criteria

Containing Fire

Interior walls, ceilings, and floors frequently play important roles in the *compartmentation* of fire, that is, in slowing fire's spread, containing the smoke and other toxic byproducts of fire, and protecting building occupants during such emergencies. For example, floor-ceiling and wall assemblies may act as barriers to the spread of fire between different building areas and levels, isolate areas with differing fire risks, protect the egress routes that occupants rely on when escaping from a building, and provide spaces where occupants can safely shelter in place during an emergency. The locations and levels of resistance to fire required for such assemblies are specified by the building code and depend not only on the nature of the activities being protected, but also on the size of the building, type of construction, presence of fire sprinklers or other safety systems, and other factors (Figure 22.3).

Fire resistance ratings are determined by full-scale endurance tests conducted in accordance with ASTM E119. In this test, the assembly is constructed in a large laboratory furnace, and the structural load, if any, for which it is designed is applied. Next, the assembly is subjected to the heat and flame of the furnace according to a standard time–temperature curve, reaching 1700 degrees Fahrenheit (925°C) at one hour and 2000 degrees Fahrenheit (1093°C) after four hours. To achieve a given fire resistance rating, measured in minutes or hours, an assembly must safely carry its design structural load for the designated period, must not develop any openings that permit the passage of flame or hot gasses, and must insulate sufficiently against the heat of the fire to limit surface temperatures on the side away from the fire. Wall and partition assemblies must also pass a *hose stream test*, which is intended to assess their durability while exposed to fire conditions. In this test, a sample of the assembly is subjected to fire exposure, then sprayed with water from a calibrated fire nozzle for a specified period. To pass this test, the assembly must not allow passage of the water stream. An example of a fire-resistance-rated partition assembly is shown in Figure 22.4. (ASTM E119 is also used to test the fire resistance of building structural components, as discussed in Chapter 1.)

Where openings or penetrations occur in fire-rated assemblies, the resistive performance of the assembly must be maintained. For example, doorways in rated partitions must themselves meet fire resistance requirements (Figure 19.23), as must glazed openings in such walls. Where HVAC ducts pass through rated assemblies, sheet metal dampers that close automatically in the presence of hot gasses, called *fire dampers*, must be inserted in the duct. And where pipes, conduit, or other service items pass through rated walls or floor-ceilings, these penetrations must also be sealed tightly with fire- and smoke-resistive *firestopping* material (Figure 22.5).

Type of Assembly	Required Fire Resistance
Enclosures for exit stairways, elevator hoistways, and other vertical shafts	2 hours where connecting four or more floors 1 hour where connecting three or fewer floors
Corridor and elevator lobby enclosures	1 hour in unsprinklered buildings; 0–1 hour in sprinklered buildings, depending on the occupancy classification and number of occupants served
Dwelling or sleeping unit separations in multi-unit residential buildings	½–1 hour, depending on construction type and presence of sprinklers
Areas of refuge	2 hours
Mall tenant separations	1 hour
Fire area and occupancy separations	0–4 hours

FIGURE 22.3
Fire resistance requirements for the containment of fire and protection of building areas, applying to both wall and floor-ceiling assemblies, summarized from the International Building Code. In the last table row, fire areas are portions of a building that are limited in area or occupant number for the purpose of determining sprinkler requirements. Rated separations between different occupancies are sometimes used to allow increased building area.

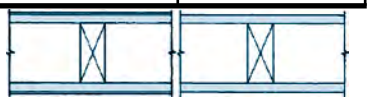
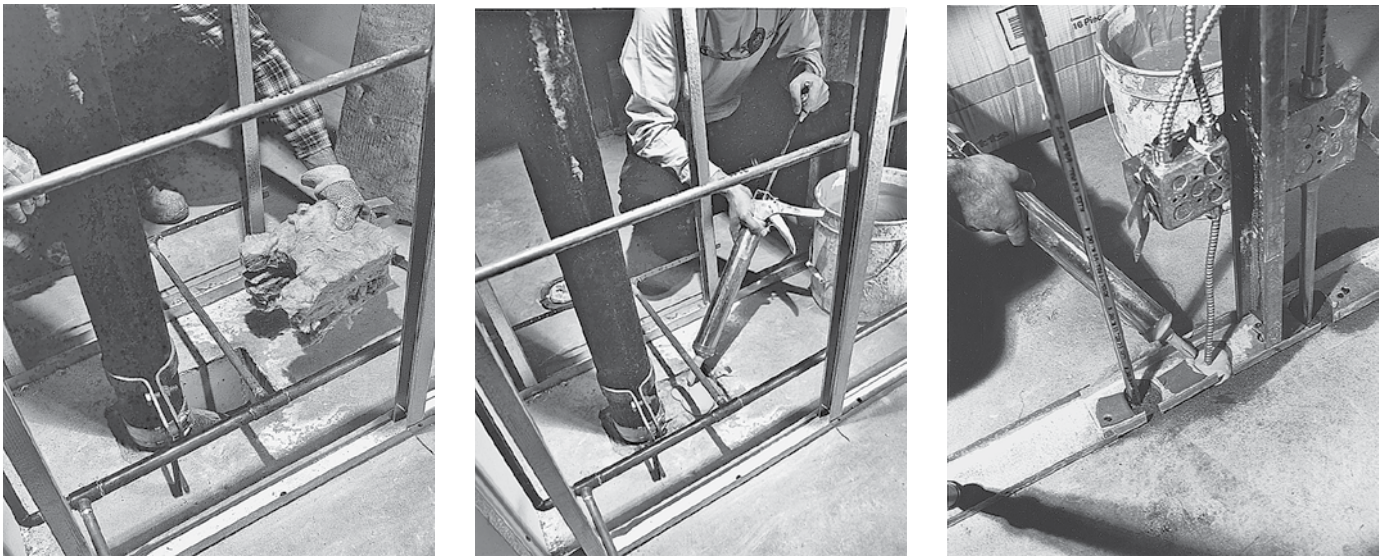
Fire Rating	Sound Rating STC	GA File No.	DETAILED DESCRIPTION	SKETCH AND DESIGN DATA: Fire / Sound
1 HR	30 to 34	WP 3620	**Construction Type: Gypsum-Veneer Base, Veneer Plaster, Wood Studs** One layer ½″ type X gypsum veneer base applied at right angles to each side of 2 × 4 wood studs 16″ o.c. with 5d etched nails, 1¾″ long, 0.099″ shank, ¼″ heads, 8″ o.c. Minimum 1/16″ gypsum-veneer plaster over each face. Stagger vertical joints 16″ and horizontal joints each side 12″. Sound tested without veneer plaster. (LB)	 Thickness: 4⅛″ Approx. Weight: 7 psf Fire Test: UC, 1-12-66 Sound Test: G & H IBI-35FT. 5-26-64

FIGURE 22.4

Fire resistance ratings can be applied to both combustible and noncombustible construction. Here, a partition constructed of wood studs, fire-resistant gypsum wallboard, and veneer plaster achieves a 1-hour rating. *(Courtesy of the Gypsum Association.)*



(*a*) (*b*) (*c*)

FIGURE 22.5

Applying firestopping materials to floor penetrations. (*a*) Within a plumbing wall, a layer of safing insulation is cut to fit and inserted by hand into a large slab opening around a cast iron waste pipe. (*b*) A mastic firestopping compound is then applied over the safing to make the opening airtight. (*c*) Applying firestopping compound around an electrical conduit at the base of a partition. *(Courtesy of United States Gypsum Company.)*

Limiting the Flammability of Interior Finishes

The building code also restricts the fire behavior of exposed interior finishes in buildings. The surface burning characteristics of interior wall and ceiling finish materials are most frequently tested in accordance with ASTM E84, also called the *Steiner Tunnel Test.* In this test, a sample of material 20 inches wide × 24 feet long (500 × 7300 mm) forms the ceiling of a rectangular furnace into which a controlled flame is introduced at one end. The time the flame takes to spread across the face of the material from one end of the furnace to the other is recorded, along with the density of smoke developed. The results of this test are given as a *flame-spread rating*, indicating the rapidity with which fire spreads across the surface of the material, and a *smoke-developed rating*, which classifies the amount of smoke generated as the material burns.

Figure 22.6 summarizes allowable flame-spread ratings for interior finish materials for various building occupancies. It assigns materials to one of three classes: A, B, or C. Class A materials are those with flame-spread ratings between 0 and 25, Class B between 26 and 75, and Class C between 76 and 200. (The scale of flame-spread numbers is established arbitrarily by assigning a value of 0 to cement–asbestos board and 100 to a red oak board.) For all three classes, the smoke-developed rating may not exceed 450.

	Sprinklered			Nonsprinklered		
Occupancies	**Exit stairways**	**Corridors**	**Other spaces**	**Exit stairways**	**Corridors**	**Other spaces**
A	B	B	C	A	A	B, C
B, E, M, R-1	B	C	C	A	B	C
F	C	C	C	B	C	C
I	A, B	A, B, C	B, C	A	A, B	B
R-2, S	C	C	C	B	B	C
R-3	C	C	C	C	C	C

FIGURE 22.6

A partial summary of IBC flame-spread rating requirements for interior wall and ceiling finish materials. In general, flame spread is more restricted in occupancies with higher life-safety risk (for example, Assembly or Institutional occupancies), in parts of the building dedicated to emergency egress (such as exit stairways and corridors), and where sprinklers are not present. Building occupancy classifications are explained in Chapter 1.

Other Surface Flammability Criteria

As an alternative to flame-spread and smoke-developed ratings, interior wall and ceiling finish materials can be tested for *room fire-growth contribution*, using the NFPA 265 standard. In this test, the finish material is mounted to several adjacent wall and ceiling surfaces, and then (as in the Steiner Tunnel Test) subjected to a flame of controlled intensities and durations. For the material to pass, flame spread and growth must be controlled, and the quantities of heat and smoke emitted must not exceed stated limits. Materials passing this test are considered comparable to ASTM E84 Class A materials. Some materials, such as textile or expanded vinyl wall coverings, foam plastics, and combustible draperies, wall hangings, or other decorative materials, are subject to additional tests or limitations.

The combustibility of many flooring materials used in exits, corridors, and areas connected to these spaces must be tested according to NFPA 253 for *minimum critical radiant flux exposure*. The purpose of this test is to ensure that flooring in essential parts of the egress system cannot be easily ignited by the radiant heat of fire in adjacent spaces. Materials must meet either Class I (most resistant to radiant heat) or Class II (moderately resistant) ratings, depending on the occupancy classification and whether or not the area is protected with an automatic sprinkler system. Some traditional flooring materials, such as solid wood, resilient materials, and terrazzo, which have historically demonstrated satisfactory performance, are not required to meet this standard. In other areas of the building, flooring materials are subject to the *pill test* (Consumer Product Safety Commission DOC FF-1), which evaluates a material's propensity for flame spread when exposed to a burning tablet intended to simulate a dropped lit cigarette, match, or similar hazard.

Fireblocking and Draftstopping of Combustible Concealed Spaces

Building codes require that concealed hollow spaces within combustible assemblies (that is, within wood-framed walls, floors, ceilings, and roofs) be internally partitioned so that fire burning within these spaces cannot rapidly spread undetected over large areas or from one floor to the next. Within combustible vertical spaces, *fireblocking* is required at every floor level, at vertical intervals of 10 feet (3 m) in tall walls, at the intersection of wall framing with floor, ceiling, and roof framing, where stair tops and bottoms meet floors, and other similar conditions. Although some of these requirements are satisfied naturally by the top and bottom plates that are a normal part of structural framing, in other cases additional materials, such as wood blocking, plywood, OSB, particleboard, gypsum board, cement fiberboard, and even some mineral-fiber or cellulose insulation products, must be used.

In a similar fashion, large, concealed, combustible horizontal spaces must be partitioned with *draftstopping*. For example, draftstopping is required in attic and floor-ceiling spaces in line with dwelling unit separations in multifamily structures, as it is within any floors, attics, and roof framing that exceed certain area limits. Specific

requirements vary with occupancy and the presence of sprinklers. The list of materials permitted for draftstopping is similar to that for firestopping. Where the depth of a framed area is too great to easily draftstop, it may also be protected with fire sprinklers within the concealed space.

Indoor Environmental Quality

Interior finish materials reside within the same environment as the building's occupants. Thus, unhealthful ingredients in these materials have the potential to adversely affect users of the building. For example, formaldehyde gas, emitted by resins and adhesives used in some manufactured wood and other building products, is a known carcinogen and irritant. A host of solvents from paints, varnishes, flooring adhesives, and other materials, capable of a range of potential health impacts, can permeate the air of a building, especially when it is new. Plasticizers and stabilizers that leach from some plastics have been identified as carcinogenic, toxic, or asthma-causing. Airborne mineral and glass fibers can irritate skin, eyes, and mucous membranes. Spores from molds and mildews that grow on moisture-sensitive materials can cause reactions from mild to severe in some portions of the population. Even ordinary construction dust can inflame respiratory passages.

Some long-recognized health hazards have been eliminated from construction materials by state or federal health regulations and only remain a concern when encountered in older buildings. Examples include lead-containing paint; asbestos fibers in plaster, flooring, or fireproofing materials; and arsenic-containing wood preservatives. More recently, heightened awareness of the presence in building materials of chemicals of concern for human health or the environment, and *indoor air quality* (*IAQ*) concerns due to materials emissions, has led to increased attention to selecting materials that are as free as possible from potential negative health impacts. This is especially true for buildings constructed to the standards of sustainability programs such as LEED, Living Building Challenge, and WELL Building (see Chapter 1 for more information about these programs).

For example, sustainability programs set low limits on the volatile organic compound (VOC) content of interior coatings, adhesives, and sealants. When these materials are field-applied in a wet state and then allowed to cure or dry, they release unhealthful compounds into the air. By limiting the VOC content of such materials, the health of the materials installers and future building occupants are better protected. These programs also require other forms of emissions testing for the full range of materials that can impact interior air quality, including, for example, insulation, wallboard, wall coverings, paints and other coatings, ceiling materials, flooring, furniture, and more. The most commonly referenced test for this purpose is the *California Department of Public Health Standard Method* (*CDPH Standard Method*). In this test, materials are placed into a sealed chamber with controlled temperature and humidity for 96 hours, during which time air is circulated and emissions are monitored. In order for a material or product to pass, the presence of unhealthful compounds must not exceed prescribed limits.

Health product disclosures and other types of materials disclosures (discussed in Chapter 1) can also assist in the selection of interior materials free from potentially harmful compounds.

Allowing for Movement

Interior finish systems must accommodate movements between themselves and surrounding building components, as well as expansion and contraction within the finishes themselves. Figure 22.7 illustrates an interior expansion joint cover that can be used to conceal a building separation joint, as may occur in a larger building, while maintaining a finished appearance and accommodating the movements that occur between the separate structural parts. As another example, as discussed in more detail in the next chapter, where nonbearing partitions meet the underside of structural slabs above, the connection must allow for deflections in the slab without imparting loads into the partition for which it is not designed (Figure 23.2 and accompanying text).

Interior finish materials also often require surface divider joints of various kinds, to conceal or limit cracking within the materials themselves due to drying, chemical curing, or changes in temperature. These types of joints are most important in rigid or brittle finish materials and when finishes extend over large areas. Various examples are included in the following chapters.

Relationship to Mechanical and Electrical Services

Interior finish materials join the mechanical and electrical services of a building at the points of delivery of the services—the electrical outlets, the lighting fixtures, the ventilating diffusers and grills, the convectors, the lavatories and water closets. Leading up to these points, the services may or may not be concealed by the finish materials. If the service lines are to be concealed, the finish systems must provide space for them, as well as for maintenance access points in the form of access doors, panels, hatches, coverplates, or ceiling or floor components that can be lifted out to expose the lines. If service lines are to be left exposed, the architect should organize them visually and specify a sufficiently high standard of workmanship in their installation so that their appearance will be satisfactory.

Changeability

How often are the use patterns of a building likely to change? In a

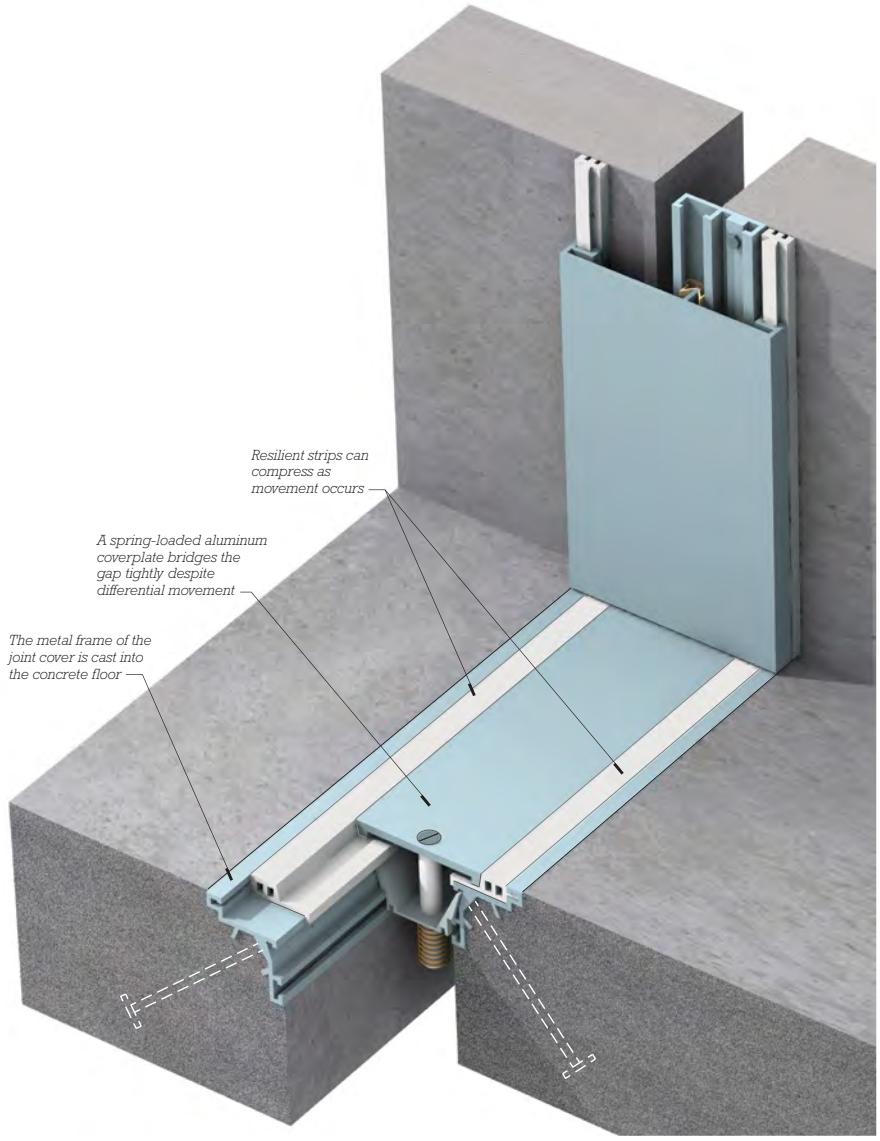


FIGURE 22.7
Building separation joints must be covered on the interior of the building to make them safe and attractive. The covers must adjust readily to movements between the separate parts of the building. Shown here are joint covers for a floor and a wall. These are designed to remain tightly in place while accommodating differential movements of any type. Firestopping (not shown here) is installed behind the joint cover to prevent the passage of smoke and fire from one floor to the next. For a general discussion of movement joints in buildings, see the Chapter 10 sidebar, "Movement Joints in Buildings." *(Courtesy of Architectural Art Manufacturing, Inc., Wichita, KS.)*

concert hall, a chapel, or a hotel, major changes will be infrequent, so fixed, unchangeable interior partitions are appropriate. Appropriate finishes include many of the heavier, more expensive, more luxurious materials (such as tile, marble, masonry, and plaster) that are considered desirable by many building owners. In a rental office building or a retail shopping mall changes will be frequent, and lighting and partitions should be easily and economically adjustable to new use patterns without long delays or unnecessary disruption. The likelihood of frequent change may lead the designer to select either relatively inexpensive, easily removed construction (such as gypsum wallboard partitions) or relatively expensive but durable and reusable construction (such as proprietary systems of modular, relocatable partitions). The functional and financial choices must be weighed for each building.

Long-Term Trends in Interior Finish Systems

Interior finish systems have undergone a transformation over roughly the past 75 years. Formerly, the installation of finishes for a commercial office began with the construction of partitions of heavy clay tiles or gypsum blocks set in mortar. These were covered with two or three coats of plaster and joined to a three-coat plaster ceiling. The floor was commonly made of hardwood strips with a wood baseboard, or perhaps of poured terrazzo with an integral terrazzo base. Today, the same office might be framed in light metal studs and walled with gypsum board. The ceiling might be a separate assembly of lightweight, acoustically absorbent tiles, and the floor might be a thin layer of carpet or

resilient tile glued to a smooth concrete slab.

Several trends can be discerned in these changes. One is away from an integral system of finishes toward one made of discrete components. In the old office, the walls, ceiling, and floor were all joined, and none could be changed without disrupting the others. In the new office, ceiling and floor finishes often extend uninterrupted from one side of the building to the other, so that partitions can be changed at will without affecting either the ceiling or the floor. The trend toward discrete components is epitomized by partitions made of modular, demountable, relocatable panels.

Another discernible trend is away from heavy finish materials to lighter ones. A partition of metal studs and gypsum board has a fraction of the weight of one of clay tiles and plaster, and a resilient tile installation is many times lighter than a traditional terrazzo one of equal area. Lighter finishes reduce the dead load the structure of the building must carry. This enables the structure itself to be lighter and less expensive. Lighter finish materials reduce shipping, handling, and installation costs, and are easier to move or remove when changes are required.

Wet systems of interior finish, made of materials mixed with water on the building site, have been largely replaced by dry ones. Plaster has been replaced by gypsum board and ceiling tiles in most areas of new buildings, and tile and terrazzo floors by resilient materials or carpet. The installation of dry systems is fast and less dependent on weather conditions. Dry systems require less skill on the part of the installer than wet systems, because the skilled work is transferred from the job site to the factory, where it is done by machines. All these differences tend to result in a lower installed cost.

Traditional finishes, however, are far from obsolete. They are long-lasting and regularly encountered when older buildings are renovated or restored. And there are still times when traditional finish materials, with their unique aesthetic qualities and long-term durability, find application in new construction as well.

MasterFormat Sections for Selecting Interior Finishes

01 84 00	**INTERIORS PERFORMANCE REQUIREMENTS**
01 84 19	Interior Finishes Performance Requirements
07 84 00	**FIRESTOPPING**
07 84 13	Penetration Firestopping
07 84 43	Joint Firestopping
07 95 00	**EXPANSION CONTROL**
07 95 13	Expansion Joint Covers

Key Terms

heating, ventilating, and air conditioning (HVAC)
shaft
decibel (dB)
dBA
Hertz (Hz)
airborne sound
structure-borne sound
Sound Absorption Average (SAA)
Noise Reduction Coefficient (NRC)
reverberation
acoustic insulation
Sound Transmission Class (STC)
sound flanking
Field STC (FSTC)
Apparent STC (ASTC)
Impact Isolation Class (IIC)
Field IIC (FIIC)
fire compartmentation
fire resistance rating
hose stream test
fire damper
firestopping
Steiner Tunnel Test
flame-spread rating
smoke-developed rating
room fire-growth contribution
minimum critical radiant flux exposure
pill test
fireblocking
draftstopping
indoor air quality (IAQ)
California Department of Public Health Standard Method (CDPH Standard Method)

Review Questions

1. Draw a flow diagram of the approximate sequence in which finishing operations are carried out on a large building of Type II-A construction.
2. List the major considerations that an architect should keep in mind while selecting interior finish materials and systems.
3. What are two important fire tests conducted on interior finish systems? What measures of performance are derived from each?
4. Describe three examples of fire compartmentation and the range of fire resistance ratings required.

Exercises

1. You are designing a 31-story residential R-2 occupancy apartment building in a large city. Assume that it will be fully sprinklered. What types of construction are you permitted to use under the International Building Code? What classes of finish materials can you use in the exit stairway? In the corridors to those stairways? Within the individual apartments? If a red oak board has a flame-spread rating of 100, can you panel an apartment in red oak? What fire resistance ratings are required for partitions between apartments? Between an egress corridor and an apartment? What type of fire door is required between the apartment and the exit corridor? What is the required fire resistance rating for the walls around the elevator shafts? For the purposes of this exercise, when referring to Figure 22.3, assume the highest rating where a range of requirements is indicated for a single condition.

2. Select two interior finish products, for example, two floor coverings, two ceiling systems, or two wall paints. From the product manufacturers' websites, download the information related to the sustainability of these products, including, for example, environmental label certifications, product disclosures, and environmental product declarations. Compare the two products and discuss their relative merits and demerits from a sustainability perspective.

Selected References

Allen, Edward, and Joseph Iano. *The Architect's Studio Companion* (6th ed.). Hoboken, NJ, John Wiley & Sons, 2017.

The fourth section of this book gives extensive information on providing space for mechanical and electrical equipment in buildings.

ARCOM, and the *American Institute of Architects. The Graphic Standards Guide to Architectural Finishes.* Hoboken, NJ, John Wiley & Sons, 2002.

This reference provides detailed information on the selection and design of many interior finish systems.

International Code Council. *International Building Code.* Falls Church, VA, updated regularly.

The reader is referred to Chapters 7 and 8 of this model code, which deal with fire-resistive construction requirements for interior finishing systems.

Websites

GreenScreen for Safer Chemicals: www.greenscreenchemicals.org

This organization provides tools for chemical hazard assessment, in order to identify chemicals of high concern in manufactured products, including those used in building construction.

Health Product Declaration Collaborative: www.hpd-collaborative.org

This organization maintains the HPD Open Standard, to encourage the transparent and reliable reporting of product contents and associated health concerns.

International Living Future Institute Red List: living-future.org/declare/declare–about/red-list

Red List chemicals are considered severely polluting, bio-accumulating, and toxic, or harmful to workers who come in contact with them during manufacture or construction.

International WELL Building Institute: www.wellcertified.com

This organization publishes the WELL Building Standard and provides resources for promoting health and wellness in buildings and communities.

23

Interior Walls and Partitions

- **Interior Walls and Fire Criteria**
  - Combustible and Noncombustible Walls
  - Fire Walls
  - Fire Barriers and Fire Partitions
  - Smoke Barriers and Smoke Partitions
- **Partition Framing**

Sustainability and Gypsum and Other Wall Covering Products

- **Plaster Partitions**
  - Gypsum Plaster
  - Portland Cement Plaster
  - Plastering
  - Lathing
  - Plaster over Expanded Metal Lath
  - Plaster over Gypsum Lath
  - Veneer Plaster
  - Plaster Direct-Applied to Masonry or Concrete
  - Plaster Partitions
- **Gypsum Board Partitions**

Plaster Ornament

  - Types of Gypsum Board
  - Installing and Finishing Gypsum Board
  - Gypsum Board Partitions
- **Masonry Partitions**
- **Wall and Partition Facings**

A plasterer applies a scratch coat of gypsum plaster to expanded metal lath. The extrusions of plaster forced through the small openings in the lath will, once the plaster dries, form a mechanical bond with the lath. The partition is framed with open-truss wire studs, a type of framing seen in older buildings but no longer used in new construction. Today, the work of skilled plasterers continues to be called on where the high surface quality and other unique attributes of a metal lath and plaster finish are desired. *(Courtesy of United States Gypsum Company.)*

There is more to interior walls and partitions than meets the eye. Behind their simple surfaces lie assemblies of materials carefully chosen and combined to meet specific performance requirements relating to structural strength, fire resistance, durability, and acoustical isolation. A partition may be framed with steel or wood studs and faced with plaster or gypsum board. Alternatively, masons may construct it of concrete blocks or structural clay tiles. For improved appearance or durability, a partition may be faced with ceramic tiles, masonry veneer, wood paneling, or any of a long list of other finish materials to tailor it to the requirements of a specific application.

Interior Walls and Fire Criteria

Combustible and Noncombustible Walls

In noncombustible construction type buildings, interior walls must also be noncombustible. This means walls and partitions must be constructed of metal studs, masonry, or concrete and covered with gypsum wallboard, plaster, or other noncombustible materials. (In some cases, wood framing chemically treated with fire-retardants may also be used.) In combustible buildings, interior walls may be made of any materials. That is, combustible wood framing and plywood or OSB sheathing are also permitted. (See Chapter 1 for more information about construction types.)

Fire Walls

A *fire wall* is a fire-resistance rated wall that extends continuously from the building foundation to the roof and between opposite exterior walls. It is used to divide a single building into smaller units, each of which may be considered as a separate building when calculating allowable heights and areas under the building code. A fire wall must either meet a noncombustible roof structure at the top or extend through and above the roof by a specified minimum distance: 30 inches (760 mm) in the case of the International Building Code (IBC). Under this code, a fire wall must also extend horizontally at least 18 inches (450 mm) beyond the exterior walls of the building unless these exterior walls meet certain fire resistance and combustibility requirements. Except in buildings of Type V construction, a fire wall must be noncombustible. It must also have sufficient structural stability during a building fire to allow collapse of the construction on one side or the other without itself collapsing. Openings in fire walls are also restricted in size and aggregate area and must be protected with fire doors. The required fire resistance ratings for fire walls under the International Building Code are tabulated in Figure 1.7.

Fire Barriers and Fire Partitions

In the International Building Code, fire-resistance rated walls used to restrict the spread of fire within a building are called *fire barriers* and *fire partitions*. Fire barriers must extend from the floor slab below to the underside of the floor or roof structure above. They may be used to separate different building occupancies, enclose shafts, and to limit the extent of *fire areas* (the size and location of fire areas within a building relate to automatic sprinkler requirements). Fire partitions are used to enclose corridors and elevator lobbies, and to separate tenant spaces in mall buildings or dwelling units in hotels, dormitories, and other multidwelling unit buildings. The requirements for fire partitions are less stringent than for fire barriers. For example, in some cases they may terminate at the underside of a suspended ceiling. A *shaft wall* is a special type of fire barrier used to enclose vertical openings that extend through multiple floors of a building, such as for elevators, exit stairs, or vertical runs of ductwork, conduits, or pipes.

Openings in fire barriers and partitions are restricted in size and must be protected with fire doors or fire-rated glass. Required fire resistance ratings for various types of fire barriers and partitions are listed in Figure 22.3.

In many circumstances, the structural elements that support fire barriers and fire partitions must have a fire resistance rating at least as great as that of the wall being supported. For example, in a building of Type II-B construction, the structure as a whole is permitted to be unprotected. However, columns, bearing walls, and other parts of the structure that support, for example, a 1-hour rated exit stairway enclosure must themselves also be protected with at least a 1-hour fire resistance rating.

Smoke Barriers and Smoke Partitions

In certain institutional occupancies such as hospitals and prisons where occupants are unable to leave the building in case of fire, interior partitions, called *smoke barriers* by the International Building Code, are required. This type of wall divides floors of buildings in such a way that occupants may take refuge in case of fire by moving to the side of the smoke barrier that is away from the fire, without having to exit the building. A smoke barrier is a 1-hour rated partition that is continuous from one side of the building to the other and from the top of a floor slab to the underside of the floor or roof slab above. It must be sealed at all edges. Doors through smoke barriers are necessary to allow movement of people in case of fire. They must be close fitting, without grilles or louvers, and must close automatically in the event of fire.

A *smoke partition* is a wall constructed, like a smoke barrier, to resist the passage of smoke, but without any fire resistance rating. For example, when walls for corridors and elevator lobbies need not be fire-rated, they are constructed as smoke partitions.

Partition Framing

Metal partition framing is directly analogous to wood light framing (see Chapter 5) but constructed of *light gauge steel studs* and *tracks* (or *runners*) made of galvanized steel sheet metal. Framing members range in depth from 1-⅝ to 6 inches (64 to 152 mm) and are formed from sheet metal 0.015 to 0.033 inches (0.38 to 0.84 mm) thick (Figures 23.1 and 23.2). Light gauge steel members and framing methods are discussed in detail in Chapter 12. Wood-framed partitions, where permitted, are constructed of nominal 2-inch (50 mm) wood light framing, as discussed in Chapter 5.

Nonloadbearing partitions must be isolated from movements in the surrounding building structure that could otherwise cause distortion of the partition framing or stresses in partition finishes. Where partitions meet structural walls or columns, resilient sealant joints are added to accommodate such movements. Where the tops of partitions abut the underside of the floor or roof structure above, *deflection tracks* (*slip tracks*) isolate the partition from movement in those elements (Figure 23.2*b*). Where the risk of seismic events is high, deflection tracks can isolate the partition from lateral movements in the building structure as well.

Where partitions do not reach to the underside of the structure above, their tops must be supported, either by connection to a suspended ceiling system or with regularly spaced members that act as lateral braces between the partitions and the structure.

When plaster or gypsum board surfaces are applied over a masonry or concrete wall, they are spaced away from the wall with either wood or metal *furring strips* (Figures 23.3, 23.4, and 23.5). Furring strips allow easier fastening of the finish materials, permit the installation of a flat wall finish over irregular surfaces, and provide a concealed space behind the finish for installing plumbing, wiring, or thermal insulation.

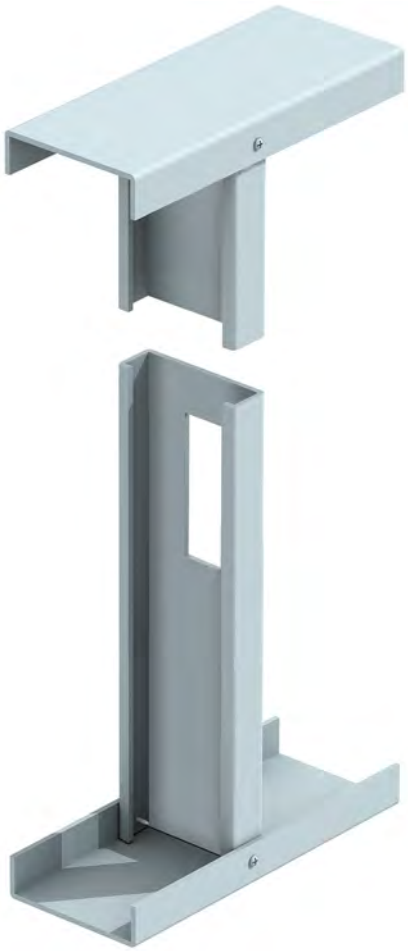
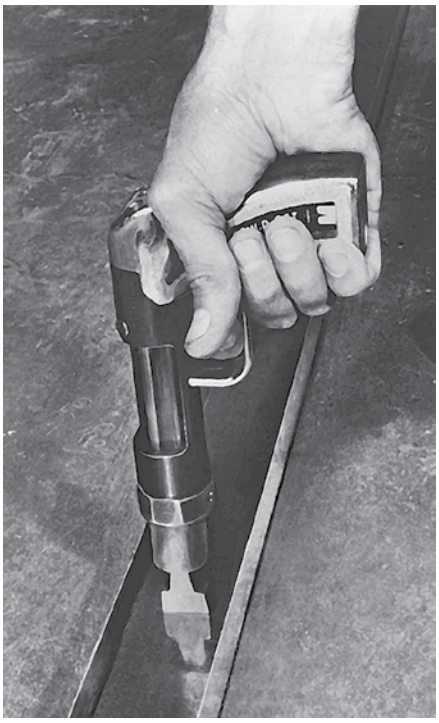
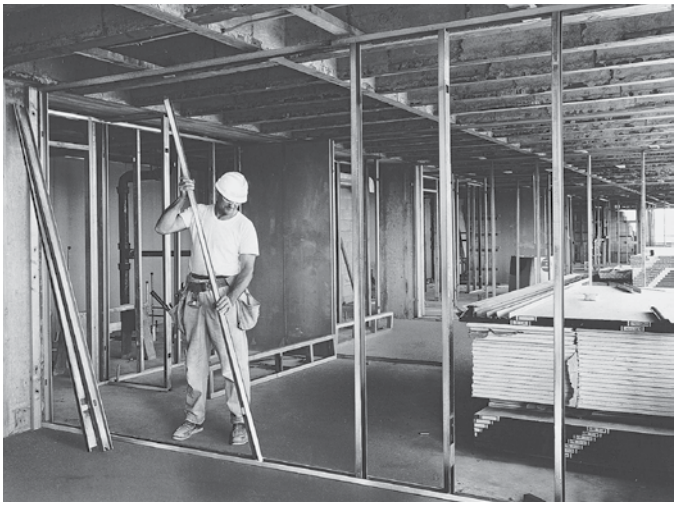


Figure 23.1
Noncombustible partitions are assembled with light gauge steel studs attached to top and bottom track sections (runners), usually with self-drilling screws. Preformed holes in the studs provide openings for wiring, small-diameter piping, or metal bracing.



(*a*)

(*b*)



(*c*)

(*d*)

FIGURE 23.2

(*a*) Attaching a runner to a concrete floor using powder-driven fasteners. The gun explodes a small charge of gunpowder to drive a steel pin through the metal and into the concrete to make a secure connection. (*b*) Where a nonloadbearing partition abuts the underside of the floor structure above, a deflection track isolates the partition from movements in the structure. A sheet metal angle connects the deflection track to a steel tab welded to the HSS steel member above. Deflection tracks can also be made by nesting one track inside another or by leaving studs unattached to the track with metal bracing added near the top of the studs to hold the studs laterally. (*c*) A twisting motion is used to ease studs into place between the top and bottom runners. The snug fit between the vertical legs of the runners and the flanges of the studs temporarily holds the studs in place until they are fastened. (*d*) Completed partition framing. *(Photos (a, c) courtesy of United States Gypsum Company; photos (b, d) by Joseph Iano.)*

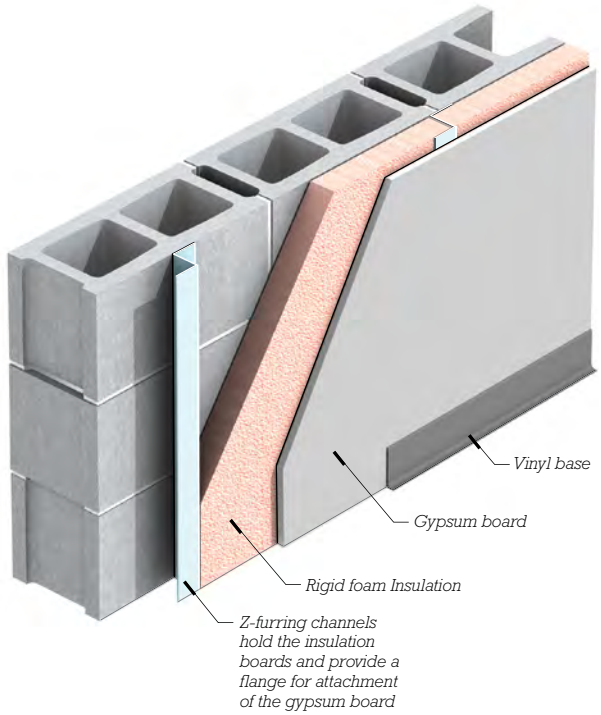


FIGURE 23.3
A furred gypsum board finish over a concrete block wall. The *Z-furring* is attached to the masonry with powder-driven fasteners. The plastic foam insulation is tucked in behind the flange of the channel, and the gypsum board is screwed to the face of the flange.

Interactive Exercise

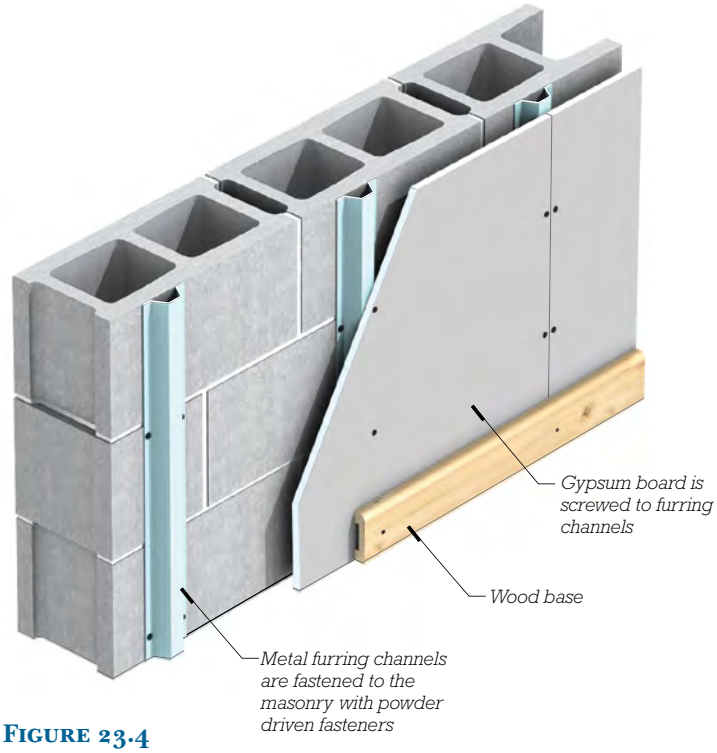


FIGURE 23.4
A furred gypsum board finish using a standard hat-shaped metal furring *hat channel*.

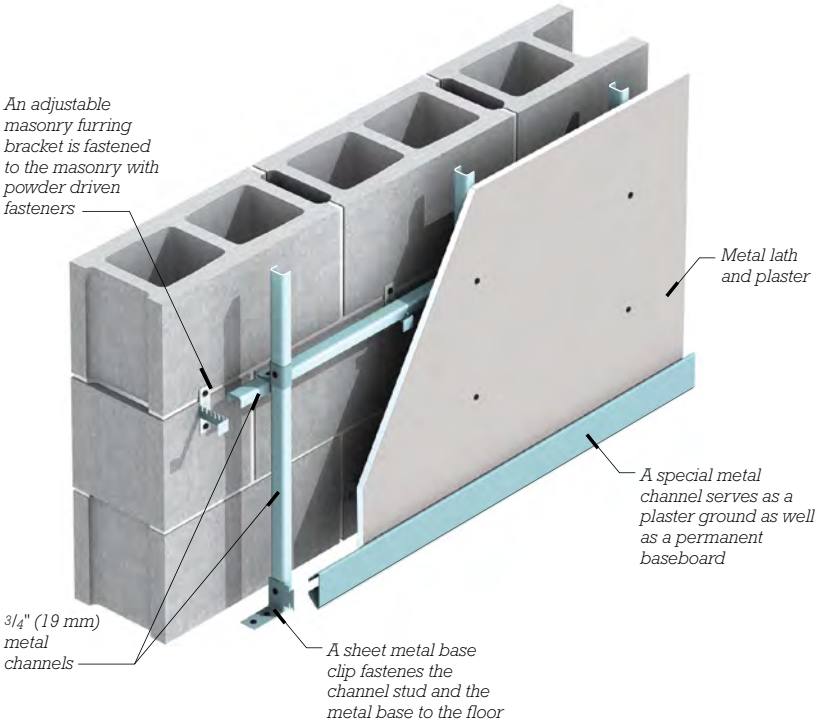


FIGURE 23.5
A furred plaster finish using adjustable brackets. Each bracket has a series of teeth along its upper edge so that a metal channel can be wired securely to it in any number of positions, allowing the lather to produce a flat wall regardless of the surface quality of the masonry.

Sustainability and Gypsum and Other Wall Covering Products

For more information about the sustainability of interior finishes, see the Chapter 22 sidebar, "Sustainability and Interior Finishes."

Building and Material Life-Cycle Impacts

- Roughly two-thirds of all gypsum board waste originates as scrap produced during new construction. The remainder comes from manufacturing waste and demolition of existing construction.
- Rates for recycling gypsum board waste into new board are low due to the costs of recycling and competition with readily available sources of synthetic gypsum. There are also technical limits on the amount of paper from waste gypsum board that can be safely introduced into new wallboard without impairing the new product's fire resistance.
- Gypsum board waste from the demolition of older buildings may be contaminated with nails, drywall tape, joint compound, and paint. The presence of these foreign materials makes this type of board waste less practical to recycle.
- More than three-quarters of recycled gypsum board waste is used an agricultural soil amendment.
- A Gypsum Association EPD reports the following North American industry average cradle-to-gate impacts per square meter (11 sq ft) of ⅝-inch (16-mm) Type X gypsum board:

Nonrenewable primary energy consumption	57 MJ (54,000 BTU)
Global warming potential	3.4 kg (7.5 lb) CO_2 eq.
Fresh water consumption	42 L (11 gal)

- In comparison to the industry averages reported in the previous item, one manufacturer's declarations for sustainably manufactured versions of the same product type report reductions of 25 percent or more in all three of these categories.

Material and Production Attributes

- Approximately 15 million tons (14 million tonnes) of gypsum board are produced in the United States each year.
- Most gypsum board contains less than 5 percent postconsumer recycled material, though some manufacturers produce products with content as high as 15 to 20 percent.
- Synthetic flue-gas desulfurization gypsum accounts for roughly half of all gypsum used in the manufacture of gypsum construction products in North America.
- Many gypsum board products are available with preconsumer recycled material content exceeding 90 percent, based on the use of synthetic gypsum in their manufacture.
- The paper facings on gypsum board products are made from 100 percent postconsumer recycled paper waste.

Unhealthful Materials and Emissions

- Dust from sanding of gypsum board finishing compounds may contain compounds associated with possible respiratory tract irritation, silicosis, and lung cancer.
- Most gypsum products have very low emissions.
- Paints, wallcovering adhesives, and other products used to finish gypsum surfaces can be significant emitters of VOCs.

Responsible Industry Practices and Social Impacts

- Naturally occurring gypsum is plentiful and widely distributed geographically. The gypsum industry estimates there are sources of natural gypsum sufficient for over 350 years of production needs.
- The majority of newly extracted gypsum is quarried in surface mines, with attendant loss of wildlife habitat, surface erosion, and water pollution, as well as the problems of disposing of overburden and mine tailings, and land restoration.
- The UL 100 standard certifies gypsum board products based on life-cycle, materials, energy use, manufacturing and operations, health and environment, and product stewardship criteria.
- The NSF/ANSI 342 standard certifies other textile, polymer, paper, and natural fiber wall covering products based on life-cycle, environmental quality, and corporate governance criteria.

Plaster Partitions

Plaster is a generic term that refers to any of a number of cement-like substances that are applied to a surface in paste form and then harden into a solid material. Plaster may be applied directly to a masonry surface or to any of a group of plaster bases known collectively as *lath* (rhymes with "math"). Plastering began in prehistoric times with the smearing of mud over masonry walls or over a mesh of woven sticks and vines to create a construction known as *wattle and daub*, the wattle being the mesh and the daub the mud. The early Egyptians and Mesopotamians developed finer, more durable plasters based on gypsum and lime. Portland cement plasters evolved in the 19th century. It is from these latter three materials—gypsum, lime, and portland cement—that the plasters used in buildings today are prepared.

Gypsum Plaster

Gypsum is an abundant mineral in nature, a crystalline hydrous calcium sulfate. It is quarried, crushed, dried, ground to a fine powder, and heated to 350 degrees Fahrenheit (175°C) in a process known as "calcining" to drive off about three-quarters of its water of hydration. The *calcined gypsum*, ground to a fine white powder, is known as *plaster of Paris*. When plaster of Paris is mixed with water, it rehydrates and recrystallizes rapidly to return to its original solid state. As it hardens, it gives off heat and expands slightly.

Synthetic gypsum is chemically identical to naturally occurring gypsum but produced from the waste products of various industrial processes. The most common type used in the manufacture of gypsum board products is *flue-gas desulfurization gypsum* (*FGD gypsum*), made from the byproduct of scrubbing sulfur dioxide emissions from the stacks of coal-fired power plants. FGD gypsum accounts for half or more of all gypsum used in the manufacture of gypsum board products in North America.

Gypsum is a major component of interior finish materials in most buildings. It has but one major disadvantage—its solubility in water. Among its advantages are that it is durable and light in weight compared to many other materials. It resists the passage of sound better than most materials. It has a very fine grain, is easily worked in either its wet or dry state, and can be fashioned into surfaces that range from smooth to heavily textured. Above all, it is inexpensive, and it is highly resistant to the passage of fire.

When a gypsum building component is subjected to the intense heat of a fire, a thin surface layer is calcined and gradually disintegrates. In the process, it absorbs considerable heat and gives off steam, both of which cool

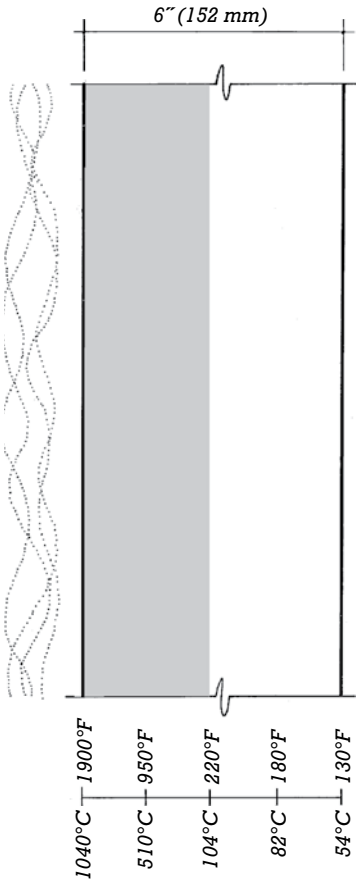


Figure 23.6
The effect of fire on gypsum, based on data from Underwriters Laboratories. After a 2-hour exposure to heat following the ASTM E119 standard time–temperature curve, less than half of the gypsum on the side toward the fire, shown here by shading, has calcined. The portions of the gypsum to the right of the line of calcination remain at temperatures below the boiling point of water.

the fire (Figure 23.6). Layer by layer, the fire works its way through the gypsum, but the process is slow. The uncalcined gypsum never reaches a temperature more than a few degrees above the boiling point of water, so areas behind the gypsum component are well protected from the fire's heat. Any required degree of fire resistance can be created by increasing the thickness of the gypsum as necessary. The fire resistance of gypsum can also be increased by adding lightweight aggregates to reduce its thermal conductivity and by adding reinforcing fibers to retain the calcined gypsum in place as a fire barrier.

For use in construction, calcined gypsum is carefully formulated with starch and other additives to control its setting time and other properties. Gypsum plaster is made by mixing the appropriate dry plaster formulation with water and an aggregate: either fine sand or a lightweight aggregate, such as perlite or vermiculite. Because of its expansion during setting, gypsum plaster (unlike portland cement plaster) is not prone to shrinkage cracking as it dries.

Gypsum plasters are manufactured in accordance with ASTM C28 and fall into two general categories: *base-coat plasters*, used for the underlying preparatory coats of a plaster application, and *finish-coat plasters*. Base-coat plasters are provided either *ready-mixed*, with aggregate added at the manufacturing plant, or *neat*, for use with aggregate added at the job site. They also come in various formulations satisfying differing requirements for application methods, strength, weight, and resistance to fire.

Finish-coat plasters are typically a blend of gypsum plaster and *lime*, with the lime improving workability and finishing qualities. (For more information about the manufacture of lime and its use in plasters, see Chapter 8.) *Ready-mixed finish plaster* comes with all ingredients factory-blended. *Gauging plaster* is a gypsum plaster that is mixed with hydrated finishing lime at the job site. Other finish plasters are formulated for higher strength, greater crack resistance, lower moisture absorbency, or greater airborne sound absorption. Retarders and accelerators can also be added on the job site to adjust the setting time to job site temperature and humidity conditions.

Portland Cement Plaster

Portland cement–lime plaster, also called *portland cement plaster* or *stucco*, relies on portland cement rather than

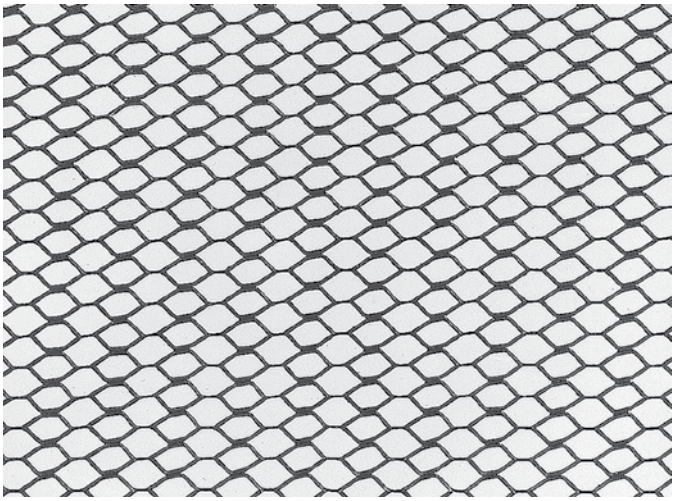
FIGURE 23.7
A plasterer with hawk in left hand and trowel in right hand. Plaster mixed to the proper consistency is placed on a board or table within easy reach. The plasterer scoops a working amount of plaster from the table onto the hawk in preparation for troweling the plaster onto the wall. *(Photo by Joseph Iano.)*

gypsum as the plaster binder, and is similar to masonry mortar. (See Chapter 8 for more about masonry mortar.) Because portland cement plaster is not damaged by water, it is used where the plaster is likely to be subjected to moisture, as on exterior wall surfaces or in commercial kitchens, industrial plants, and shower rooms. Because the freshly mixed plaster is not as buttery and smooth as gypsum and lime plasters, it is usually finished with a rougher-textured surface finish. Because the portland cement shrinks slightly during curing, this type of plaster is prone to shrinkage cracking and requires more attention to placement of joints for control of cracking.

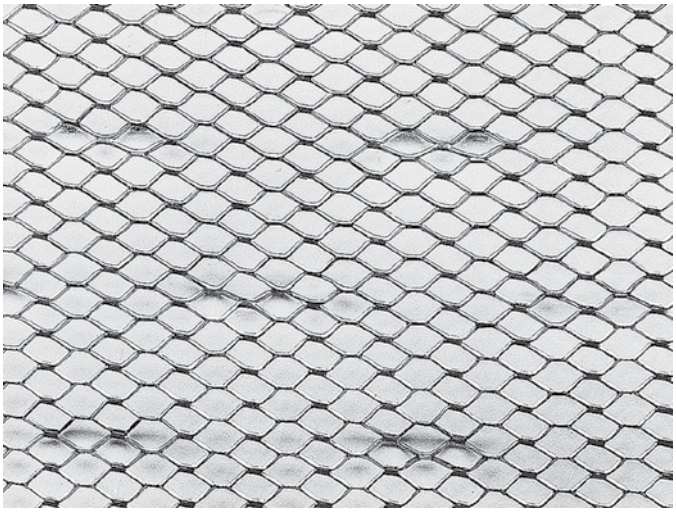
Plastering

Plaster can be applied either by machine or by hand. Machine application is essentially a spraying process. Hand application is done with two very simple tools: a *hawk* in one hand to hold a quantity of plaster ready for application and a *trowel* in the other hand to lift the plaster from the hawk, apply it to the surface, and smooth it into place (Figures 23.7 and 23.8). Plaster is transferred from the hawk to the trowel with a quick, practiced motion of both hands, and the trowel is moved up the wall or across the ceiling to spread the plaster, much as one uses a table knife to spread soft butter. After a surface is covered with plaster, it is leveled by drawing a straightedge called a *darby* across it, after which the trowel is used again to smooth the surface.

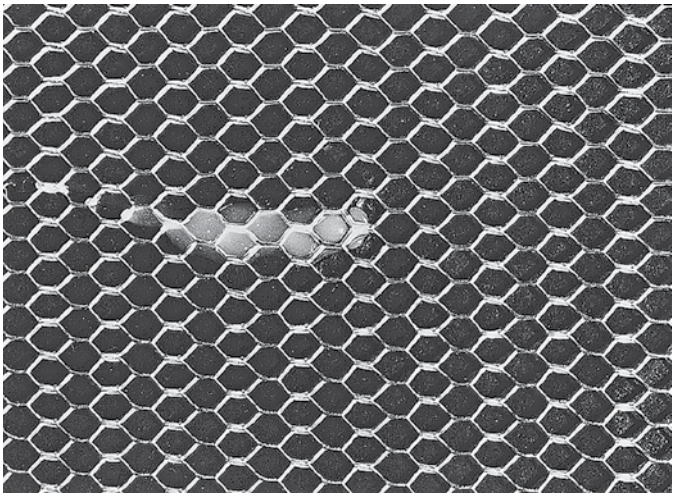
Figure 23.8
With a single deft motion, the plasterer transfers plaster from the hawk to the trowel and then from the trowel to the wall surface. In this image, a plaster scratch coat is being applied to compound curved metal lath. *(Photo by Joseph Iano.)*



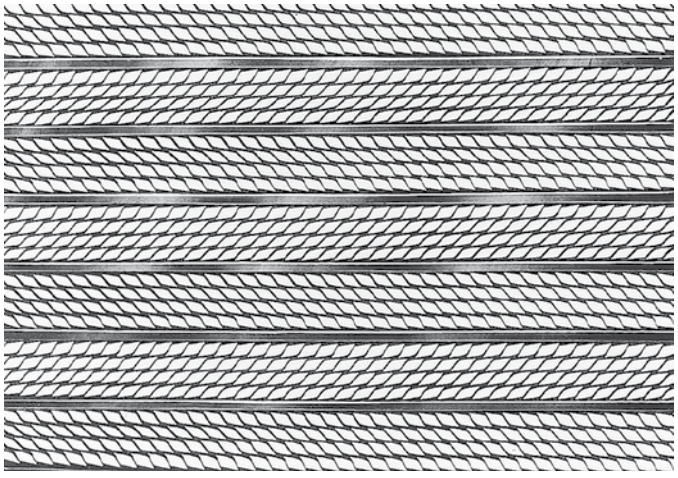
(*a*)



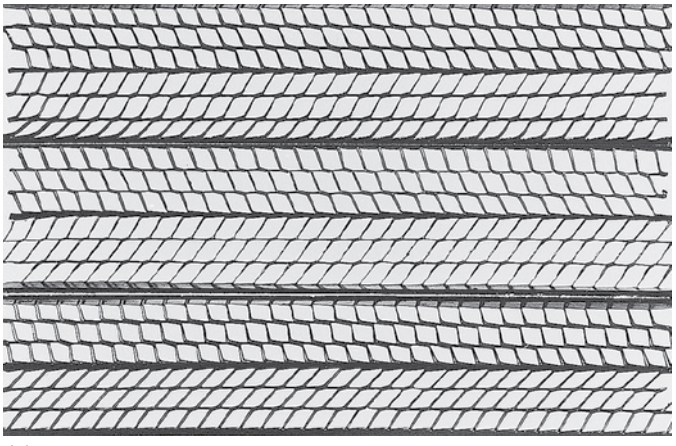
(*b*)



(*c*)



(*d*)



(*e*)

FIGURE 23.9

Five types of expanded metal lath. (*a*) General-purpose diamond-mesh expanded metal lath. (*b*) Self-furring diamond-mesh metal lath. Dimples in the lath space it away from solid sheathing behind to allow plaster to key through the openings in the mesh. (*c*) Paper-back lath, used for backup walls beneath ceramic tile and for exterior stucco. The water-resistant paper discourages moisture that seeps through the plaster from penetrating further into the wall. (*d*) Four-mesh Z-riblath is stiffer than ordinary diamond-mesh lath, making it suitable for ceilings. (*e*) Three-eighths-inch (10-mm) riblath has V-shaped ribs for exceptional rigidity; it is used for ceilings or concrete formwork where supports are widely spaced. *(Courtesy of United States Gypsum Company.)*

Lathing

Historically, the most common form of lath consisted of thin strips of wood nailed to wood framing with small spaces left between the strips to allow *keying* of the plaster. Most lath today is made of either expanded metal or preformed gypsum boards. The skilled tradesperson who applies lath and trim accessories is known as a *lather*.

Expanded metal lath is made from thin sheets of steel that are slit and stretched in such a way as to produce a mesh of diamond-shaped openings (Figure 23.9). It is applied to light gauge steel studs with *self-drilling, self-tapping screws* or to wood studs with large-headed *lathing nails*. Lath used with portland cement stucco, and likely to be used in a damp exposure, is galvanized to resist corrosion.

Gypsum lath is made in gypsum board sheets (see discussion later in this section) that are usually 16 × 48 inches (406 × 1220 mm) and ⅜ inch (9.5 mm) thick. The sheets consist of hardened gypsum plaster faced with outer layers of a special absorbent paper to which fresh plaster readily adheres and inner layers of water-resistant paper to protect the gypsum core. Gypsum lath is attached to steel or wood studs with screws (Figure 23.10). Gypsum lath cannot be used as a base for portland cement plaster.

Veneer plaster base (*gypsum veneer base*) is a paper-faced gypsum board that comes in sheets 4 feet (1220 mm) wide, 8 to 14 feet (2440 to 4270 mm) long, and ½ to ⅝ inch (13 to 16 mm) thick. It is screwed to wood or steel studs, or nailed to wood studs, and used as a base specifically for the application of gypsum veneer plaster (discussed later in this section).

Various *lathing trim accessories*, most frequently made of galvanized steel, are used at the edges of a plaster surface to make a neat, durable edge or corner (Figure 23.11). These are installed by the lather at the same time as the lath. In long or tall plaster surfaces, metal *control joint* accessories are mounted over seams in the lath at predetermined intervals to control cracking. Trim accessories are also designed to act as lines that gauge the proper thickness and plane of the plaster surface. In this role, the accessories function as *grounds* over which a straightedge is run to level the wet plaster. Trim accessories are made in several different thicknesses to match the required plaster thicknesses over the different types of lath.

Trim accessories are also produced as extrusions of plastic or aluminum. The aluminum accessories and some of the plastic ones are designed for improved precision and appearance when used in innovative details for bases, edges, and shadow lines in plaster walls.

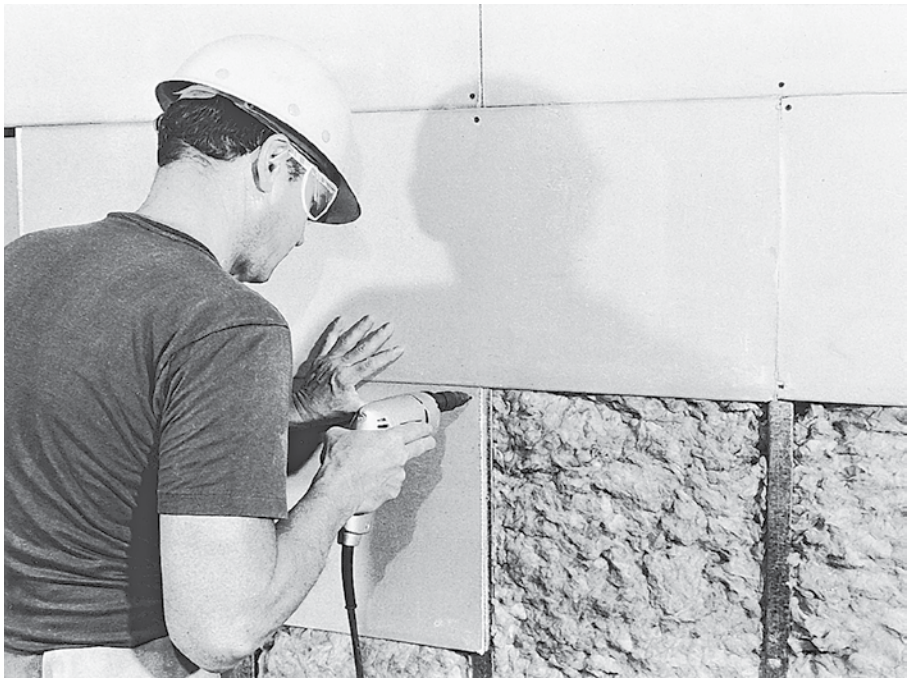


FIGURE 23.10
Installing gypsum lath over light gauge steel studs with self-drilling, self-tapping screws. The electric screw gun disengages automatically from the screw head when the screw has reached the proper depth. *(Courtesy of United States Gypsum Company.)*

In lathing I was pleased to be able to send home each nail with a single blow of the hammer, and it was my ambition to transfer the plaster from the board to the wall neatly and rapidly. . . . I admired anew the economy and convenience of plastering, which so effectually shuts out the cold and takes a handsome finish. . . . I had the previous winter made a small quantity of lime by burning the shells of the *Unio fluviatilis*, which our river affords.

—Henry David Thoreau, *Walden*, 1854

USG Corner Beads, Trim, Control Joints

description

USG Corner Beads and Trim, made from top-quality galvanized steel, enjoy the industry's top acceptance because of their dependability and continual improvement in design. Corner beads are available in 8 and 10-ft. lengths, metal trim in 7 and 10-ft. lengths, casing beads in 7, 8 and 10-ft. lengths.

1-A Expanded Corner Bead has 2⅞″ wide expanded flanges that are easily flexed. Preferred for irregular corners. Provides increased reinforcement close to nose of bead. Made from galvanized steel or zinc alloy for exterior applications.

X-2 Corner Bead has full 3¼″ flanges easily adjusted for plaster depth on columns. Ideal for finishing corners of structural tile and rough masonry. Has perforated stiffening ribs along expanded flange.

4-A Flexible Corner Bead is an economical general-purpose bead. By snipping flanges, this bead may be bent to any curved design (for archways, telephone niches, etc.).

800 Corner Bead gives 1/16″ grounds needed for one-coat veneer finishes. Approx. 90 keys per lin. in. provide superior bonding and strong, secure corners. The 1¼″ fine-mesh flange eliminates shadowing, is easily nailed or stapled.

900 Corner Bead is used with two-coat veneer systems, gives 3/32″ grounds. Its 1¼″ fine-mesh flange can be either stapled or nailed. Provides superior plaster key and eliminates shadowing.

Cornerite and Striplath are strips of painted Diamond Mesh Lath used as reinforcement. **Cornerite** is bent lengthwise in the center to form a 100° angle. It should be used in all interior angles where metal lath is not lapped or carried around, over non-ferrous lath anchored to the lath, and over internal angles of masonry constructions to reduce plaster cracking. Sizes: 2″ × 2″ × 96″ and 3″ × 3″ × 96″. **Striplath** is a similar flat strip, used as a plaster reinforcement over joints of non-metallic lathing bases and where dissimilar bases join; also to span pipe chases. **Size:** 4″ × 96″.

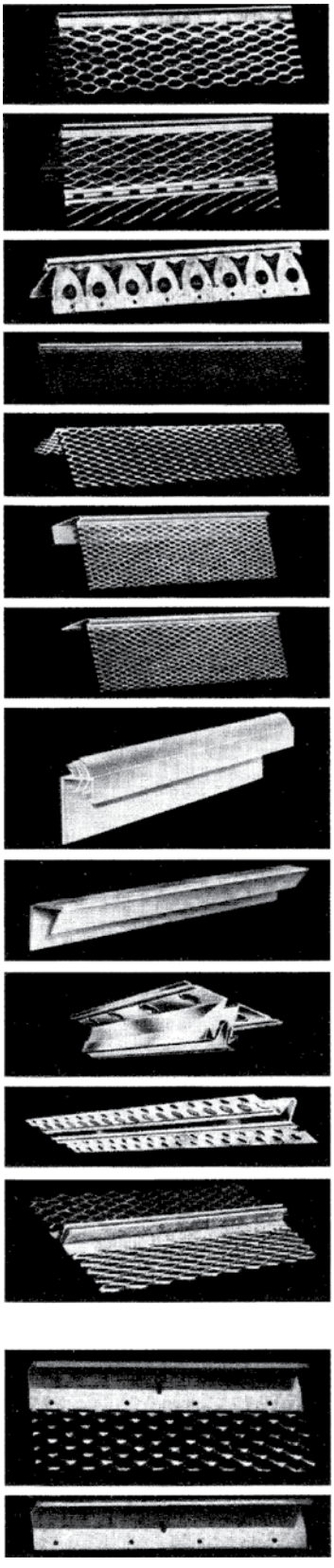
USG Metal Trim comes in two styles and two grounds to provide neat edge protection for veneer finishing at cased openings and ceiling or wall intersections. All have fine-mesh expanded flanges to strengthen plaster bond and eliminate shadowing. **No. 701-A,** channel-type, and **No. 701-B,** angle edge trim, provide 3/32″ grounds for two-coat systems. **No. 801-A,** channel-type, and **No. 801-B,** angle edge trim, provide 1/16″ grounds for one-coat systems. Sizes: for ½″ and ⅝″ IMPERIAL Gypsum Base.

USG P-1 Vinyl Trim is a channel-shaped rigid trim with flexible vinyl fins which compress on installation to provide a positive acoustical seal comparable in performance to one bead of acoustical sealant. For veneer finish partition perimeters. **Lengths:** 8, 9 and 10 ft. Sizes: for ½″ and ⅝″ gypsum base.

USG P-2 Vinyl Trim is a channel-shaped vinyl trim with a pressure-sensitive adhesive backing for attachment to the wall at wall-ceiling intersections. Provides positive perimeter relief in radiant heat and veneer finish systems. Allow ⅛″ and ¼″ clear space for insertion.

Length: 10 ft.

USG Control Joint relieves stresses of expansion and contraction in large plastered areas. Made from roll-formed zinc, it is resistant to corrosion in both interior and exterior uses with gypsum or portland cement plaster. An open slot, ¼″ wide and ½″ deep, is protected with plastic tape which is removed after plastering is completed. The perforated short flanges are wire-tied to metal lath, screwed or stapled to gypsum lath. Thus the plaster is key-locked to the control joint, which not only provides plastering grounds but can also be used to create decorative panel designs. **Limitations:** Where sound and/or fire ratings are prime considerations, adequate protection must be provided behind the control joint. USG Control Joints should not be used with magnesium oxychloride cement stuccos or stuccos containing calcium chloride additives. **Sizes and grounds: No. 50, ½″; No. 75, ¾″; No. 100, 1″** (for exterior stucco curtain walls)—10-ft. lengths.



Plaster over Expanded Metal Lath

Plaster is applied over expanded metal lath in three coats (Figure 23.12). The first, called the *scratch coat*, is troweled on rather roughly and cannot be made completely flat because the uncoated lath moves in and out under the pressure of the trowel (see the chapter opening photograph and Figure 23.8). This first coat is scratched while still wet, using a notched darby, a broom, or a special rake, to create a rough surface to which the second coat can bond mechanically (Figure 23.13).

After the scratch coat has hardened, it works together with the lath as a rigid base for the second application of plaster, which is called the *brown coat*. The purpose of the brown coat is to build strength and thickness and to present a level surface for the application of the third or finish coat. The level surface is

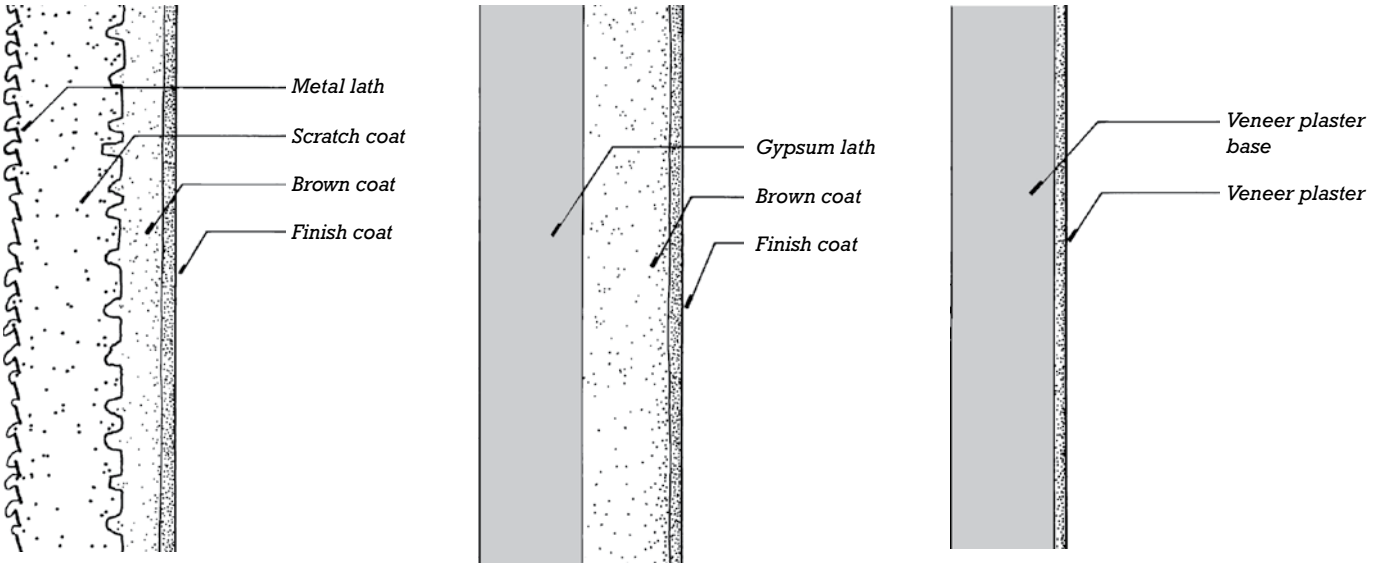


FIGURE 23.12
Sections through the three common lath-and-plaster systems, reproduced at full scale. Metal lath (*left*) requires three coats of plaster; the surface of the first coat is scratched for a better bond to the second coat. Gypsum lath (*middle*) may be finished with three coats or with two, as shown. Veneer plaster (*right*) usually consists of only a single thin finish coat, although two thin coats may be applied over rougher or more uneven substrates, such as concrete masonry and sitecast concrete.

FIGURE 23.13
Scratching the scratch coat while it is still soft to create a better bond to the brown coat. *(Courtesy of United States Gypsum Company.)*

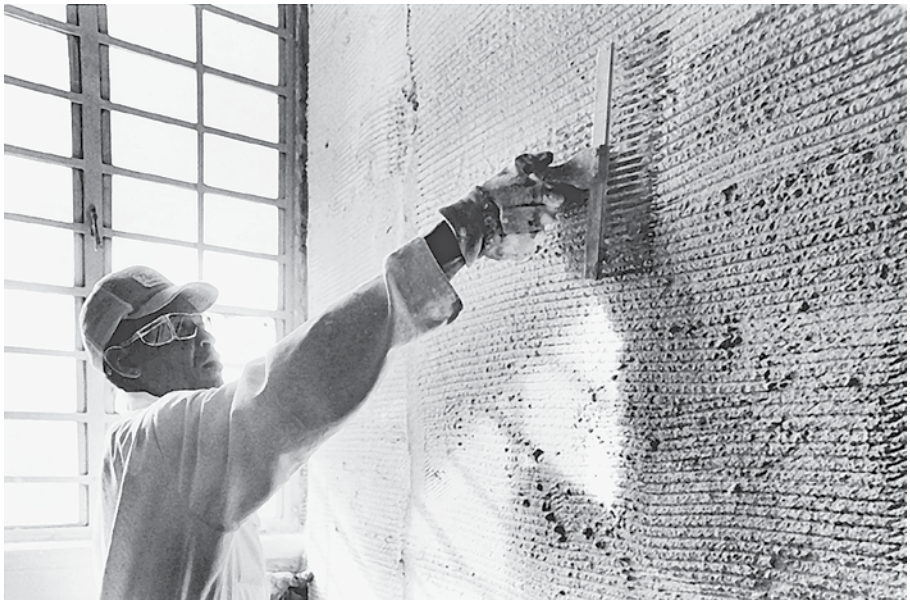


FIGURE 23.11
(*Opposite page*) Trim accessories for lath and plaster construction, as manufactured by the United States Gypsum Company. *(Courtesy of United States Gypsum Company.)*

produced by drawing a long straightedge across the surfaces of the grounds to strike off the wet plaster. On large, uninterrupted plaster surfaces, *plaster screeds*, intermittent spots or strips of plaster, are leveled up to the grounds in advance of brown coat plastering to serve as intermediate reference points for setting the thickness of the plaster during the striking-off operation. Base-coat plasters are used for scratch coats and brown coats.

The *finish coat* is a very thin application of finish-coat plaster, about 1/16 inch (1.5 mm) thick. It may be troweled smooth or worked into any desired texture (Figure 23.14). The total thickness of the plaster that results from this three-coat process, as measured from the face of the lath, is about 5/8 inch (16 mm). Three-coat work over metal lath is the premium-quality plaster system, extremely strong and resistant to fire. The only disadvantage of three-coat plaster work is its cost, which can be attributed largely to the labor involved in applying the lath and the three separate coats of plaster.

Portland cement plaster is applied over galvanized metal lath with galvanized steel trim accessories. Or, in wet areas and in exterior applications, more corrosion-resistant solid zinc or plastic accessories are used. The plaster is applied in three coats over the lath, with a total thickness of approximately 7/8 inch (22 mm). Whereas gypsum plaster expands during hardening, stucco shrinks and is prone to cracking as it dries. Stucco walls are therefore provided with control joints at more closely spaced intervals as compared to gypsum plaster walls. The curing reaction in stucco is the same as that of concrete and is very slow relative to that of gypsum plaster. Stucco must be kept moist for a week before it is allowed to dry in order to attain maximum hardness and strength through full hydration of its portland cement binder.

FIGURE 23.14
A sponge-faced float can be used to create various rough surface textures on plaster. Where a smooth surface is desired, a metal trowel is used. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

Plaster over Gypsum Lath

The best plaster work over gypsum lath (Figure 23.12) is applied in three coats, but gypsum lath is sufficiently rigid that if it is firmly mounted to the studs, only a brown coat and a finish coat need be applied. The elimination of the scratch coat has obvious economic advantages. Even with three coats of plaster, gypsum lath is often less expensive than metal lath because the gypsum in the lath replaces much of the plaster that would otherwise have to be mixed and applied by hand in the scratch coat. The total thickness of plaster applied over gypsum lath is 1/2 inch (13 mm).

Veneer Plaster

Veneer plaster is the least expensive of the gypsum plaster systems and is competitive in price with gypsum board finishes in many regions. The veneer base and accessories create a very flat surface that can be finished with a layer of a specially formulated dense gypsum plaster (manufactured to the separate standard, ASTM C587) that is applied in one, or occasionally two, coats usually no more than 1/16 to 1/8 inch (1.6 to 3.2 mm) in total thickness (Figures 23.12, 23.15, and 23.16). A typical single-coat application is applied in a "double-back" process in which a thin coat is followed immediately by a second skim coat that is finish-troweled to the desired texture. The plaster veneer hardens and dries so rapidly that it may be painted the following day. A two-coat application of veneer plaster can also be directly applied to surface of sitecast concrete or concrete masonry walls.

Plaster Direct-Applied to Masonry or Concrete

Where gypsum or portland cement plaster is applied directly over brick, concrete masonry, or cast concrete, the walls are dampened thoroughly in advance to prevent premature dehydration of the plaster. A bonding agent may be applied to some smooth surfaces to ensure good adhesion of the plaster. The number of coats of plaster required to cover a wall is determined by the degree of unevenness of the masonry surface. For the best work, three coats totaling 5/8 to 3/4 inch (16 to 19 mm) may be applied, but for many walls two coats, with a thickness of approximately 3/8 to 1/2 inch (10 to 13 mm) will suffice (Figure 23.17).

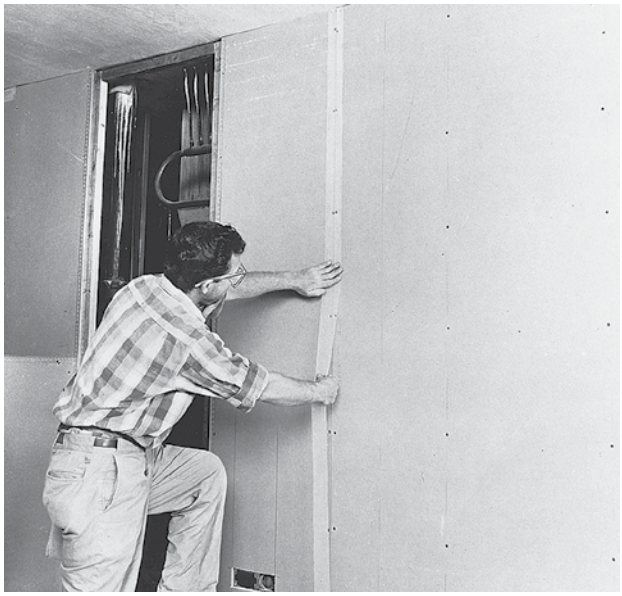


FIGURE 23.15
Reinforcing the panel joints of veneer plaster base with a self-adhesive glass fiber mesh tape. A panel opening for access to mechanical equipment is visible behind the installer.

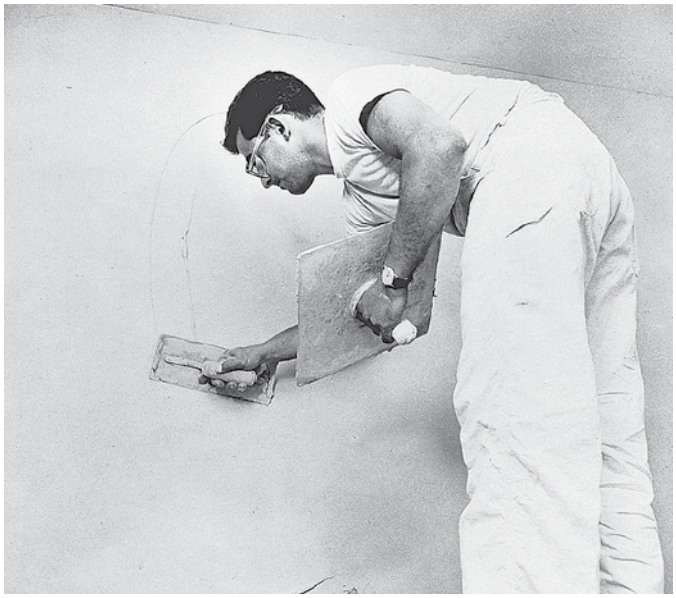


FIGURE 23.16
Applying veneer plaster with a hawk and trowel.

FIGURE 23.17
Applying a finish coat of portland cement plaster over a concrete masonry partition. The block joints are visible through the plaster brown coat because of a difference in the rate of water absorption between the blocks and the mortar joints. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th ed.; photo from Portland Cement Association, Skokie, IL.)*

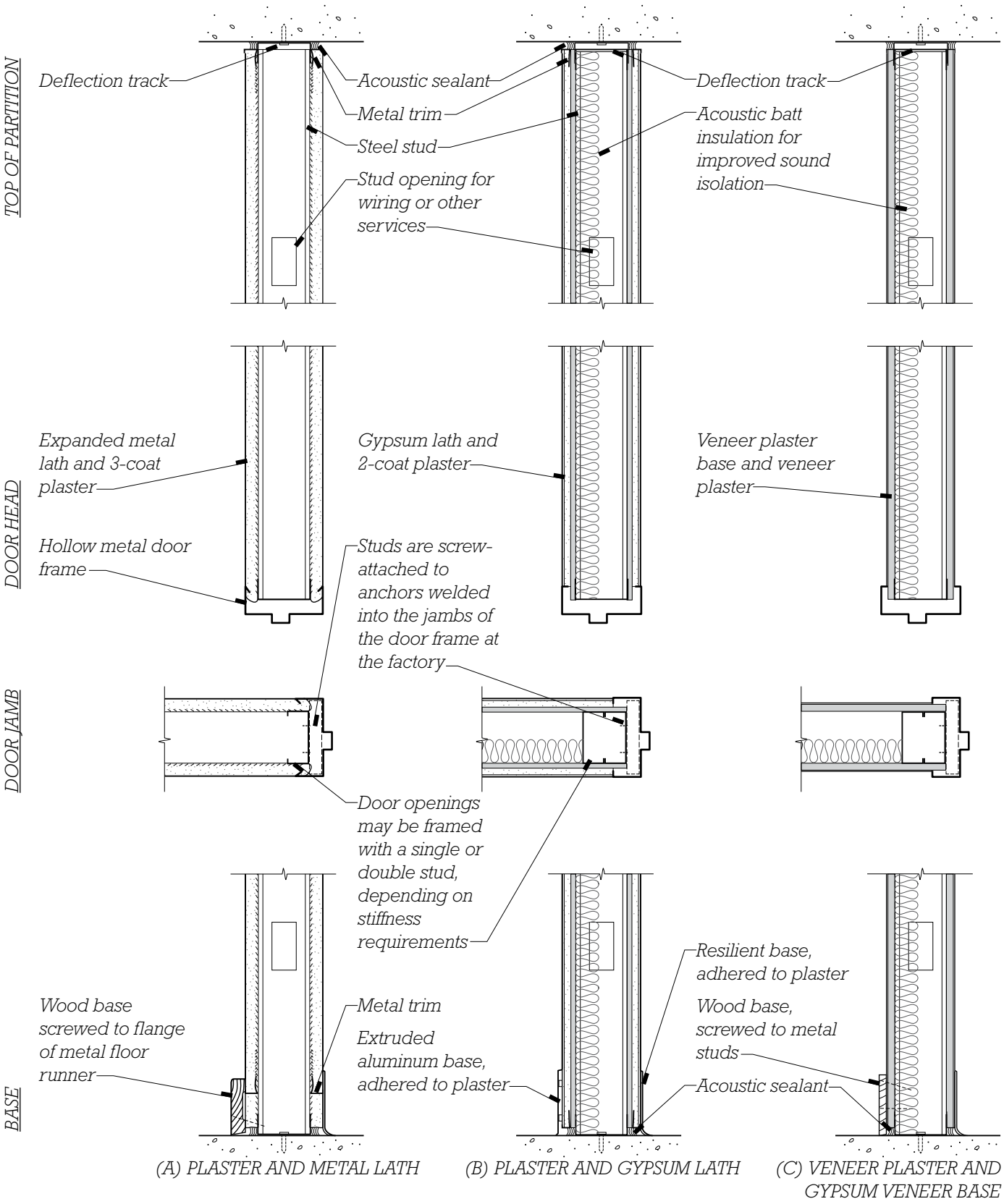


FIGURE 23.18

Three gypsum plaster partitions. (*A*) Three-coat plaster over expanded metal lath. (*B*) Two-coat plaster over gypsum lath. (*C*) Veneer plaster over veneer plaster base. All three partitions are capable of achieving a 1-hour fire resistance rating and STC ratings in the range of 40 to 50.

Plaster Partitions

Plaster partitions can achieve fire-resistance ratings as high as 4 hours, with STC ratings over 60 in metal-framed walls or 50 in wood-framed walls. The plane of the wall can be made very flat, or when constructed with metal lath, it can be formed into compound curves or curves of very small radius. The plaster surface itself is hard, durable, and uniform and can be finished textured or very smooth. Plaster surfaces can also provide an acoustically reflective surface, a property that can be exploited in the design of stage, theater, and auditorium spaces.

Three gypsum plaster partitions are detailed in Figure 23.18, illustrating plaster over metal lath, plaster over gypsum lath, and veneer plaster. In all three examples, acoustic seals are installed between the plaster edges and the adjacent structural surfaces. These are essential to acoustical performance. Without them, airborne sound can readily pass around the edges of the plaster, into and through the partitions. The top tracks are configured so that the partitions are isolated from movements in the structure above. (See Figure 23.2 and its caption for an explanation.) Framing around door openings may vary with the size and weight of the door. For smaller, lighter doors, only a single jamb stud may be needed. For larger, heavier doors, double studs, or stiffer studs made of thicker sheet metal, may be used. Metal edge trim accessories provide edge protection and serve as grounds, helping to establish a consistent plaster thickness. For improved acoustic performance, *acoustic batt insulation* may be inserted within the framing cavities. Where partitions are fire rated, fire-stopping is frequently added at the partition tops and at penetrations, to maintain the continuity of the fire protection at these locations. Though not illustrated here, plaster systems can be applied over wood framing as well.

Gypsum Board Partitions

Gypsum board is a prefabricated plaster sheet material that is manufactured in widths of 4 feet (1220 mm) and lengths of 8 to 14 feet (2440 to 4270 mm). It is also known as *gypsum wallboard*, *plasterboard*, and *drywall*. (The term "Sheetrock" is a registered trademark of one manufacturer of gypsum board.)

Gypsum board is the least expensive of all interior finishing materials for walls and ceilings. For this reason alone, it has found wide acceptance throughout North America as a substitute for plaster in buildings of every type. It retains the fire-resistive characteristics of gypsum plaster, but it is installed with less labor by less skilled workers than lathers and plasterers. And because it is installed largely in the form of dry materials, it eliminates some of the construction delay associated with the curing and drying of plaster.

The core of gypsum board is formulated as a slurry of calcined gypsum, starch, water, pregenerated foam to reduce the density of the mixture, and other additives. This slurry is sandwiched between special paper faces and passed between sets of rollers to reduce it to the desired thickness. Within two or three minutes, the core material has hardened and bonded to the paper faces. The board is cut to length and heated to drive off residual moisture, then bundled for shipping (Figure 23.19).

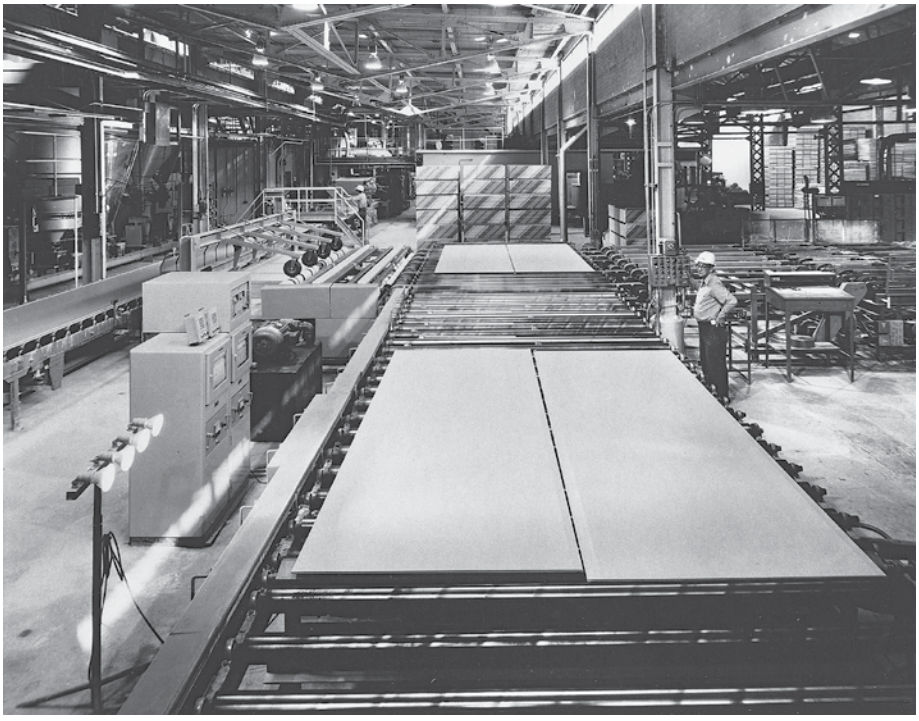


Figure 23.19
Sheets of gypsum board roll off the manufacturing line, trimmed and ready for packaging. *(Courtesy of United States Gypsum Company.)*

Plaster Ornament

Gypsum plaster, with its fine grain and even texture, has more sculptural potential than perhaps any other material used in architecture. While wet, it is easily formed with trowels and spatulas, molds, or templates. When dry, it is readily worked by sawing, sanding, machining, and carving. Plaster building ornament has been created for many centuries by two economical but powerful techniques, *casting* and *running*, and continues to be used in buildings of every size and every historical style.

Cast plaster ornament is made by pouring soupy plaster into molds. The plaster hardens in a few minutes, allowing the mold to be stripped and reused (Figure A). Both rigid molds and soft rubber molds are used. The rubber molds are very flexible, so even undercut shapes can be cast without encountering difficulties in mold removal. Traditional rubber molds are created by first carving a plaster original, then brushing layers of latex over the original to build up the required wall thickness. More recently, two-component synthetic rubber compounds have replaced latex in most applications; their advantage is that they can be spread over the original in a single application rather than in layers.

Cast ornament is adhered to the brown coat of plaster in walls and ceilings with gobs of wet plaster or a mixture of plaster and glue. Once the ornament has been securely fastened in place, the finish coat of plaster is applied around it, and the plaster surfaces and adjacent pieces of ornament are merged by skillful trowel work and sanding to create a single-piece finish.

Running is used to make linear ornaments (*run plaster ornament*) such as classic cornice moldings (Figure B). A rigid blade made of sheet metal or sheet plastic is cut to the profile of the molding. The blade is attached to a sliding wooden frame to create a template. The template is pushed back and forth along a guide strip mounted temporarily on the wall or ceiling while a mixture of lime putty and gauging plaster is inserted in front of the blade, which strikes it off to the desired profile. Repeated passes of the template are required to finish the molding smoothly and perfectly. These passes must be completed before the plaster begins to harden, or the setting expansion of the gypsum will cause the template to bind and spoil the plaster surface. The template may also be attached to a radius guide to produce circular moldings (Figures C and D).

Casting and running are often used to reproduce plaster ornament during restoration of historic buildings. Rubber molds for casting can be made directly from existing ornaments, and templates for running duplicates of existing profiles are easily and cheaply produced.

New designs for plaster ornament are readily translated from the architect's drawings into carved plaster originals, from which rubber molds are made and duplicates

Figure A
Removing the flexible rubber mold from a cast plaster ornament. *(Courtesy of Dovetail, Inc.)*

Figure B
Running a plaster cornice molding in place. *(Courtesy of Dovetail, Inc.)*

cast. New profiles for moldings are quickly converted into template blades. The possibilities are almost limitless.

Cast plaster ornament can be reinforced with short fibers of alkali-resistant glass. These greatly increase its strength and toughness and allow it to be produced in thinner sections and in larger pieces than unreinforced plaster. This recent development has dramatically changed the economics and methods of ornamentation in plaster that is based on stock designs. A number of manufacturers issue catalogs of stock designs for ornaments made by this process. Much of the on-site assembly work for elaborate ornaments can be eliminated by combining what were formerly a number of small, thick, brittle castings into a single, larger, thinner casting that is light in weight and highly resistant to breakage. On the construction site, the lightweight castings are glued in place over gypsum board or veneer plaster base using an ordinary mastic adhesive. The edges of the ornaments are feathered into the wall or ceiling surfaces with joint compound or veneer plaster, and the joints between pieces of ornament are smoothed over and sanded.

FIGURE C
Sculptor David Flaharty runs a circular plaster medallion on a bench in his shop. *(Photo © Brian McNeil.)*

FIGURE D
A close-up of Flaharty's blade and template. The template rides on the sledlike runner of the portion under his hand, which is called the "slipper." The long portion of the template, called the "stock," is a radius guide that is fastened to a pin at the end to create the circular form of the medallion. *(Photo © Brian McNeil.)*

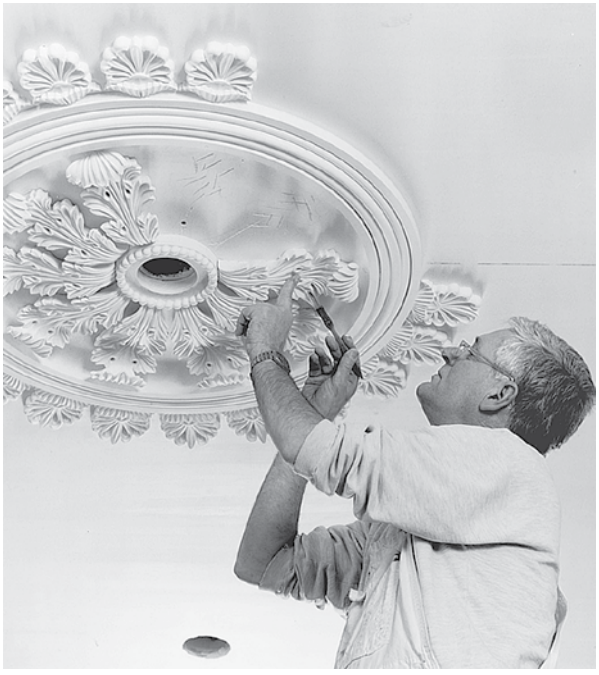


FIGURE E
The medallion having been removed from the bench and glued in place on the ceiling, Flaharty adds cast components to complete the ornament. *(Photo © Brian McNeil.)*

Types of Gypsum Board

Gypsum board is produced in many types, suitable to a wide range of requirements. *Type X gypsum board* is used in fire-rated assemblies. It is reinforced with short glass fibers that prolong the board's integrity when exposed to fire. *Moisture-resistant gypsum board* is faced with water-repellent paper or glass fiber mat and has a moisture-resistant core. It is used in locations exposed to moderate amounts of moisture that could be damaging to ordinary board. *Abuse-resistant* and *impact-resistant gypsum boards* are manufactured with heavier or reinforced facings, reinforced cores, and/or plastic film backings. They are used where greater resistance to rough usage, denting, or penetration is needed. *Mold-resistant gypsum board* combines moisture-resistant cores with chemically treated facings that are resistant to mold growth, or with strengthened cores that eliminate the need for facings of any kind. It is used where moisture or humidity conditions increase the risk of organic growth.

The most common board thickness is ½ inch (13 mm). It can be applied to studs and joists spaced up to 24 inches (610 mm). Also common is ⅝-inch (16-mm) board, used where additional fire resistance, stiffness, durability, or sound deadening is required. Thinner boards are sometimes used for tight-radius bends, in multilayered applications, or where weight savings are a priority, such as manufactured housing. A 1-inch (25 mm) thick board, called *shaft liner*, is used in shaft wall construction (Figure 23.32).

Gypsum board is manufactured with a variety of edge profiles along its longer sides. The most common by far is the *tapered edge*, which permits sheets to be joined with a flush, invisible seam by means of subsequent joint finishing operations. Rounded and beveled edges are useful in predecorated panels, and tongue-and-groove edges serve to join shaft liner panels in concealed locations. The edges of the shorter ends of gypsum board panels are not tapered or shaped, as the individual panels are cut from longer continuous sheets during manufacturing.

FIGURE 23.20
Attaching gypsum board to studs with a screw gun. *(Courtesy of United States Gypsum Company.)*

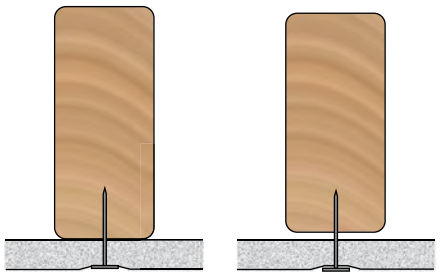


FIGURE 23.21
When wood studs dry and shrink during a building's first heating season, nail heads may pop through the surface of gypsum board walls. *(Courtesy of United States Gypsum Company.)*

Installing and Finishing Gypsum Board

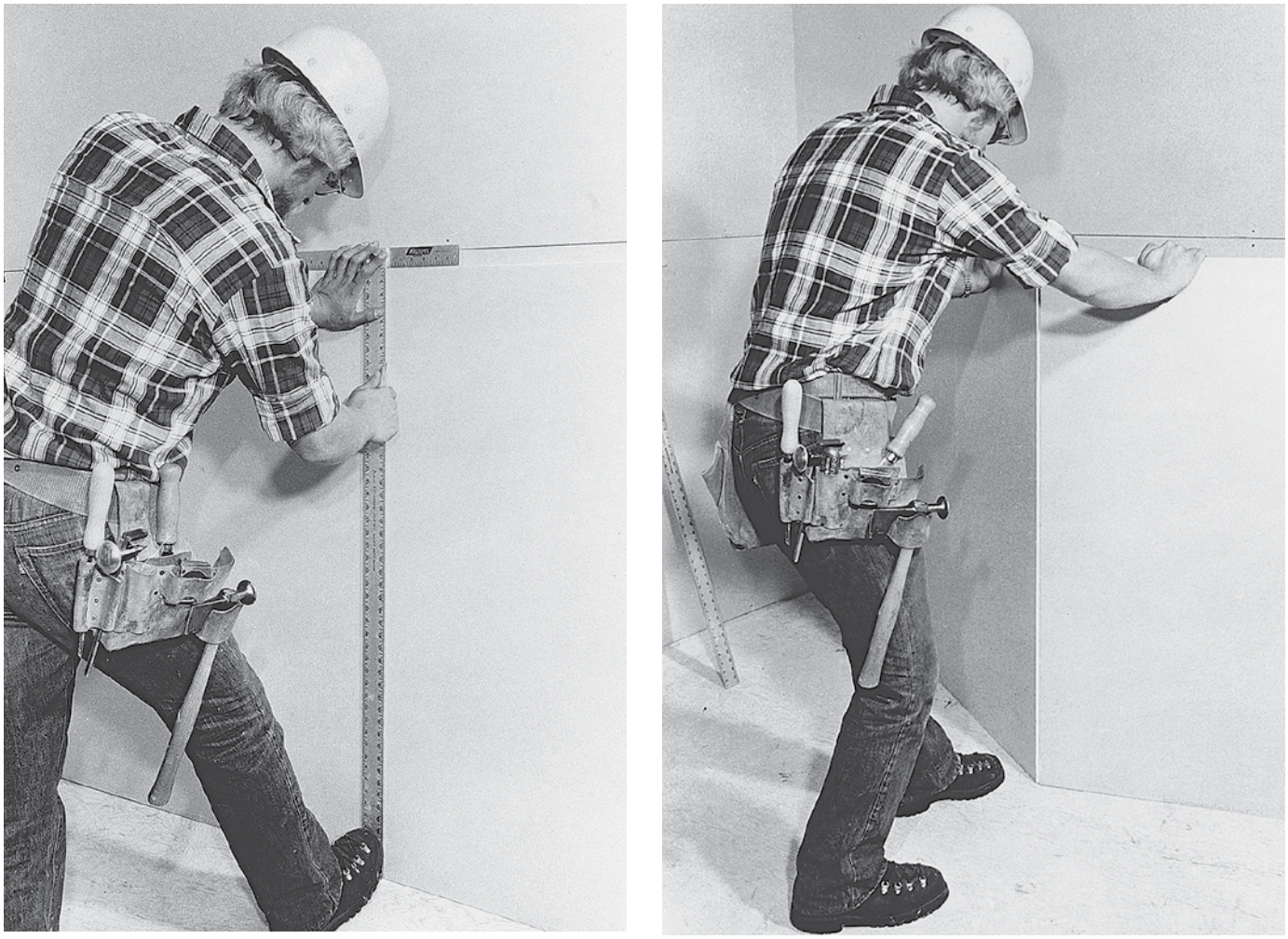
Hanging the Board

Gypsum board may be installed over either wood or light gauge steel studs, using self-drilling, self-tapping screws to fasten to steel and either screws or nails to fasten to wood (Figure 23.20). Wood studs can be troublesome with gypsum, as they usually shrink somewhat after the board is installed, causing nails to loosen slightly and pop through the finished surface of

the board (Figure 23.21). This *nail popping* can be minimized by using fully dried framing lumber, ring-shank nails that have extra gripping power in the wood, and the shortest nail that will do the job. Screws have less of a tendency to pop than nails. When screws or nails are driven into gypsum board, their heads are driven to a level slightly below the surface of the board but not enough to tear the paper surface.

To minimize the length of joints that must be finished and to create the stiffest wall possible, gypsum board is usually installed with the long dimension of the boards horizontal. The longest possible boards are used to minimize end joints between boards, which are difficult to finish because the ends are not tapered. Gypsum board is cut rapidly and easily by scoring one paper face with a utility knife, snapping the brittle core along the score line with a blow from the heel of the hand, and cutting the other paper face along the fold created by the snapped core (Figure 23.22). A large metal T-square is used to make straight cuts that are perpendicular to the edges of the board. Notches, irregular cuts, and holes for electric boxes are made with a small handsaw or small electric router.

When two or more layers of gypsum board are installed as a single surface, the joints between layers are staggered to create a stiffer, flatter wall, and a mastic adhesive may be used to fully join the layers to one another. Adhesive is also sometimes used between the studs and gypsum



(*a*) (*b*)

FIGURE 23.22

Cutting gypsum board. (*a*) A sharp knife and metal T-square are used to score a straight line through one paper face of the panel. (*b*) The scored board is easily "snapped," and the knife is used a second time to slit the second paper face. *(Courtesy of United States Gypsum Company.)*

board in single-layer installations to make a stronger assembly.

Gypsum board can be curved when a design requires it. For gentle curves, the board can be bent into place dry (Figure 23.23). For somewhat sharper curves, the paper faces are moistened to decrease the stiffness of the board before it is installed. When the paper dries, the board regains its original stiffness. Special high-flex ¼-inch (6-mm) board is available that can be bent dry to even smaller radii.

Metal trim accessories are required at exposed edges and external corners to protect the brittle board and present a neat edge (Figure 23.24). These are similar to lathing accessories for plaster.

Finishing the Joints and Fastener Holes

Joints and the surface dents at fasteners in gypsum board are finished to create the appearance of a monolithic surface almost indistinguishable from plaster. The finishing process is based on the use of a *joint compound* that resembles a smooth, sticky plaster. For most purposes, a *drying-type joint compound* is used. This is a mixture of marble dust, binder, and admixtures, furnished either as a dry powder to be mixed with water or as a premixed paste. In some high-production commercial work, *setting compounds* that cure rapidly by chemical reaction are used to minimize the waiting time between applications. Joint compounds differing in strength and other characteristics may be used for different stages of the joint finishing process, or a single all-purpose compound may be used for all steps. *Lightweight joint compounds*, weighing as much as 40 percent less than all-purpose compounds and used in the later finishing stages, reduce installer fatigue and sand easily. *Dustless*, or *dust control*, *joint compounds* reduce fine residue when the compounded surface is sanded by causing the sanding residue to bind into larger, heavier particles that fall more quickly to the floor rather than remaining suspended in the air.

The finishing of a joint between panels of gypsum board begins with the troweling of a layer of joint compound into the tapered edge joint and the bedding of a paper reinforcing tape in the compound

FIGURE 23.23
Gypsum board can be curved to a large radius by simply bending it around a curving line of studs. *(Courtesy of United States Gypsum Company.)*

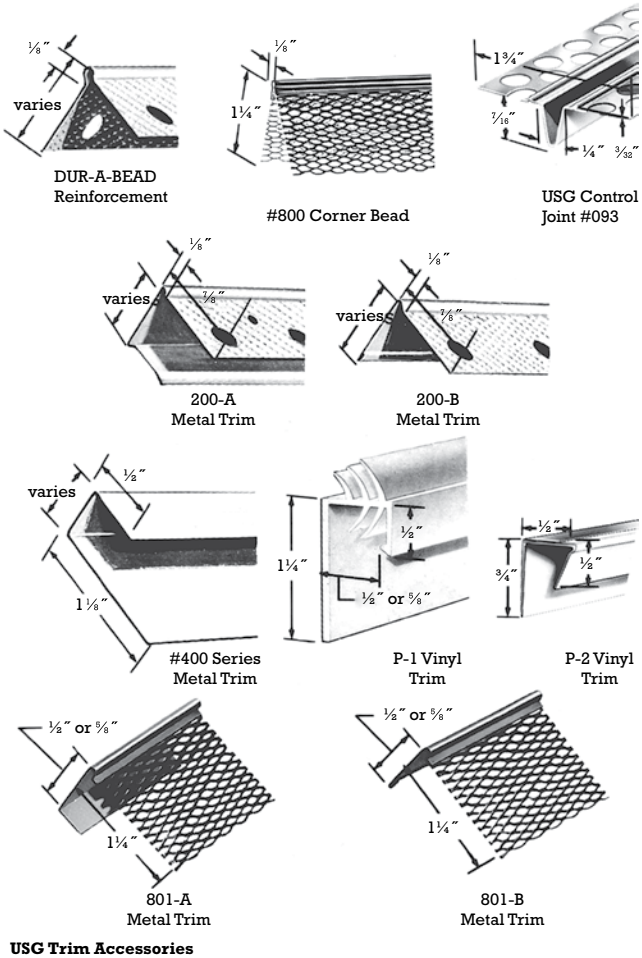


FIGURE 23.24
Accessories for gypsum board construction, as manufactured by the United States Gypsum Company. *(Courtesy of United States Gypsum Company.)*

(Figures 23.25 through 23.28). Compound is also troweled over the nail or screw holes. After drying (usually overnight), a second layer of compound is applied to the joint to bring it level with the face of the board and to fill the space left by the slight drying shrinkage of the joint compound. When this second coat is dry, the joints are lightly sanded before a very thin final coat is applied to fill any remaining voids. The final coat is feathered out (tapered down to zero thickness) to create an invisible edge. Before painting, the wall is again sanded lightly to remove any roughness or ridges. If the finishing is done properly, the painted or papered wall will show no signs at all that it is made of discrete panels of material.

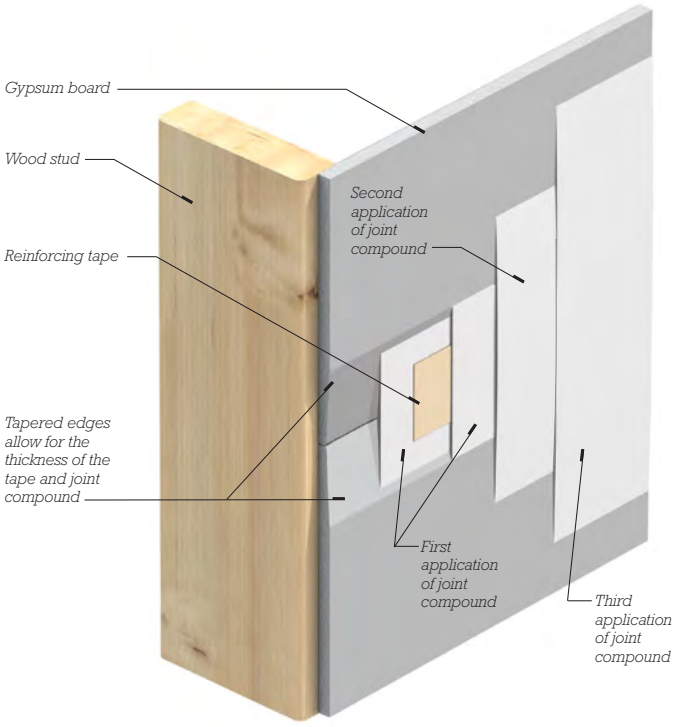


FIGURE 23.25
Finishing a joint between panels of gypsum board. *(Courtesy of United States Gypsum Company.)*

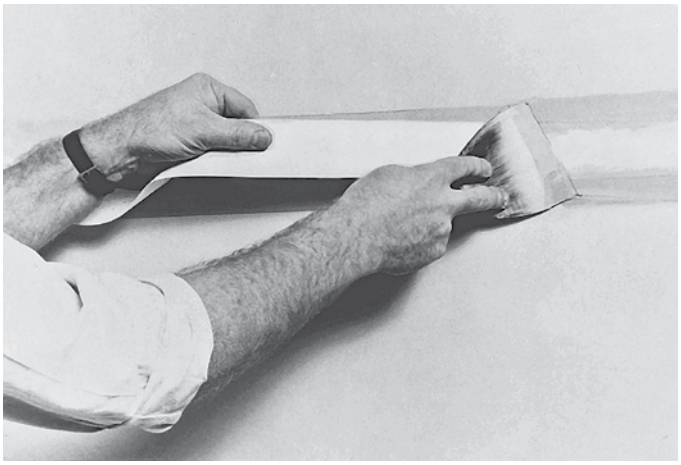


FIGURE 23.26
Applying paper joint reinforcing tape to gypsum board. *(Courtesy of United States Gypsum Company.)*

FIGURE 23.27
A drywall finisher uses a broad taping knife to apply joint compound to gypsum wallboard edges around a door opening. The pair of small, rectangular holes in the wallboard to the right of the opening are for electrical boxes that will house lighting controls. In the background, wallboard taping and finishing have been completed in a tall gallery space. Once the compound is dry and has been lightly sanded, the wall is ready for painting. *(Photo by Joseph Iano.)*

Standardized gypsum board *finish levels* are specified in ASTM C840. These enable the designer to quickly and simply indicate the minimum level of finish that is acceptable for any surface.

- Level 0 consists of just the boards, without taping, finishing, or accessories. It is used for temporary construction or where finishing is postponed until a later date.
- Level 1 requires only that joints be covered with tape set in joint compound. It is used in areas of the building that are not exposed to view, such as above suspended ceilings, in attics, and in service corridors. Level 1 is also the minimum finish level for fire-resistance-rated gypsum board assemblies, in which applications it may also be referred to as *fire-taping*.
- Level 2 adds to a Level 1 finish a coat of joint compound over the accessories and fasteners. After joint tape is set in compound, these joints are also immediately wiped with a joint knife a second time to add a thin coat of compound over the tape. A Level 2 finish is appropriate in garages, warehouses, and storage areas, and for boards used as a backing for ceramic tile.
- Level 3 adds a full second coat of compound over tape, accessories, and fasteners after the first coat has dried. It is intended for surfaces that will be textured or covered with heavy wallcoverings.
- Level 4 is the most commonly specified finish for exposed surfaces. It adds a third distinct coat of joint compound over taped seams, fasteners, and accessories. It is best used for surfaces to be finished with flat paints, light textures, or thin wallcoverings.
- Level 5 adds a very thin *skim coat* of joint compound over the entire surface of the board. The skim coat has no measurable thickness. Its purpose is to create a surface that is uniform in texture and absorption, minimizing telegraphing of the joint treatment through the final wall finish. It is recommended for surfaces that will receive gloss or semigloss paints and for surfaces that will be lit in such a way as to cast shadows that can highlight even slight imperfections.

A rougher finish surface may also be created with spray-on textures or textured paints. In residential work, ceilings are often textured to conceal the minor irregularities in workmanship that occur because of the difficulty of working in an overhead position.

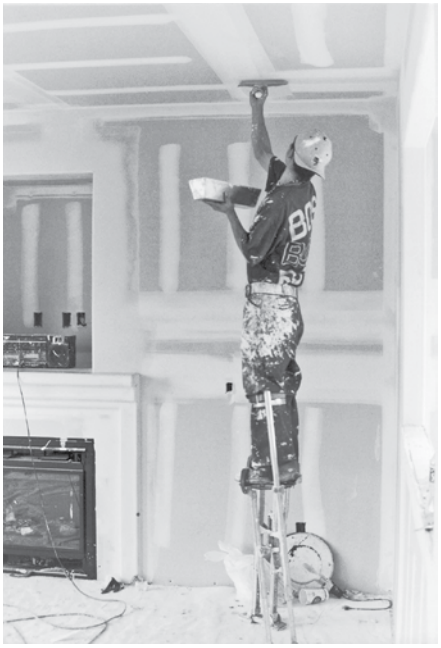


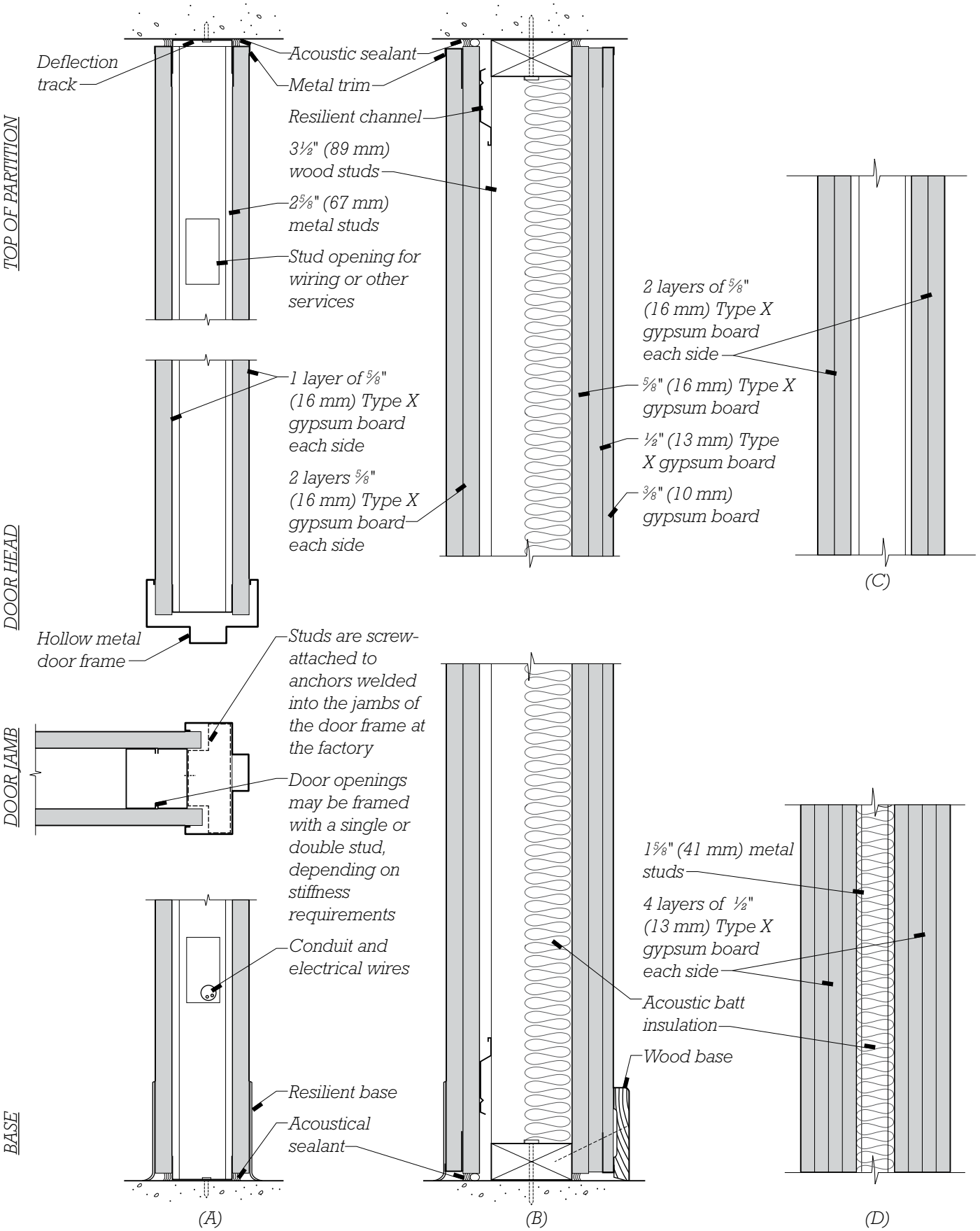
Figure 23.28
Plasterers and drywall finishers often work on stilts to avoid having to erect and move scaffolding. *(Photo by Rob Thallon.)*

Gypsum Board Partitions

Partitions constructed of gypsum board fastened over wood or metal framing are easy and fast to construct, lightweight, and inexpensive. They can be designed to meet a broad range of requirements as well as provide backing for many other surfaces such as wood paneling, stone, acoustic materials, or, with special board types, water-resistant finishes in wet areas.

The details in Figure 23.29 illustrate how the number and thickness of board layers, and method of attachment, can be varied to achieve fire resistance ratings up to 4 hours and STC ratings up to approximately 65. Like the plaster partitions discussed previously, where acoustic performance is a requirement, acoustic insulation batts are added to the partition cavity (Figure 23.30) and acoustic seals are applied at wallboard edges and penetrations. Partitions must be isolated from movements in the surrounding structure, such as with deflection tracks at partition tops. Framing around door openings must be made stiff enough to support the weight of the door and resist the force of its operation. And trim accessories are used to provide protection and a neat finish at exposed board edges.

Figure 23.29
Examples of gypsum board partition systems. (*A*) A 1-hour partition, STC 40, using Type X gypsum board over light gauge steel studs. (*B*) This 1-hour partition on wood studs achieves an STC of 60 to 64 through heavy laminations of gypsum board, a sound attenuation blanket, and resilient channel mounting for one face of the partition. (*C*) A 2-hour partition with an STC of 48. (*D*) A 4-hour partition, STC 58. (Firestopping that may be needed at the tops of partitions is not shown.)


TOP OF PARTITION
DOOR HEAD
DOOR JAMB
BASE
Deflection track
Acoustic sealant
Metal trim
Resilient channel
3½" (89 mm) wood studs
2⅝" (67 mm) metal studs
Stud opening for wiring or other services
1 layer of ⅝" (16 mm) Type X gypsum board each side
2 layers ⅝" (16 mm) Type X gypsum board each side
Hollow metal door frame
Studs are screw-attached to anchors welded into the jambs of the door frame at the factory
Door openings may be framed with a single or double stud, depending on stiffness requirements
Conduit and electrical wires
Resilient base
Acoustical sealant
2 layers of ⅝" (16 mm) Type X gypsum board each side
⅝" (16 mm) Type X gypsum board
½" (13 mm) Type X gypsum board
⅜" (10 mm) gypsum board
1⅝" (41 mm) metal studs
4 layers of ½" (13 mm) Type X gypsum board each side
Acoustic batt insulation
Wood base
(A)
(B)
(C)
(D)

Where partitions must be rearranged at frequent intervals, *demountable partition systems* of gypsum board, using concealed mechanical fasteners that can be disassembled and reassembled easily without damage to the panels, are used (Figure 23.31).

FIGURE 23.30
Installing a dense, mineral-fiber sound attenuation blanket. Conventional glass fiber insulation batts are also sometimes used for this purpose. *(Courtesy of United States Gypsum Company.)*

FIGURE 23.31
Two examples of relocatable (demountable) partition systems. (*Courtesy of United States Gypsum Company.)*

Gypsum Shaft Walls

Gypsum shaft wall systems are used to construct gypsum partitions around vertical shafts, such as for elevators, mechanical and electrical service chases, and stairways (Figures 22.1 and 23.32). The unique configuration of parts allows these walls to be constructed working only from the outside of the shaft, eliminating any need for scaffolding or suspended staging within the shaft itself. The most commonly used framing components include *J-runners* at the base, tops, and corners, and *C–H studs* spaced at 24 inches (610 mm) on center. Shaft liner panels, 1 inch (25 mm) thick, are installed into the back of the framing (closest to the shaft). Standard Type X panels are fastened to the face of the framing (on the non-shaft side) and finished with joint compound in the same manner as ordinary gypsum partitions. Fire resistance ratings up to 4 hours and STC ratings up to approximately 60 are possible. Shaft wall partitions for elevators must also be made stiff enough to resist the air pressure fluctuations that occur as elevator cabs travel up and down in the hoistway.

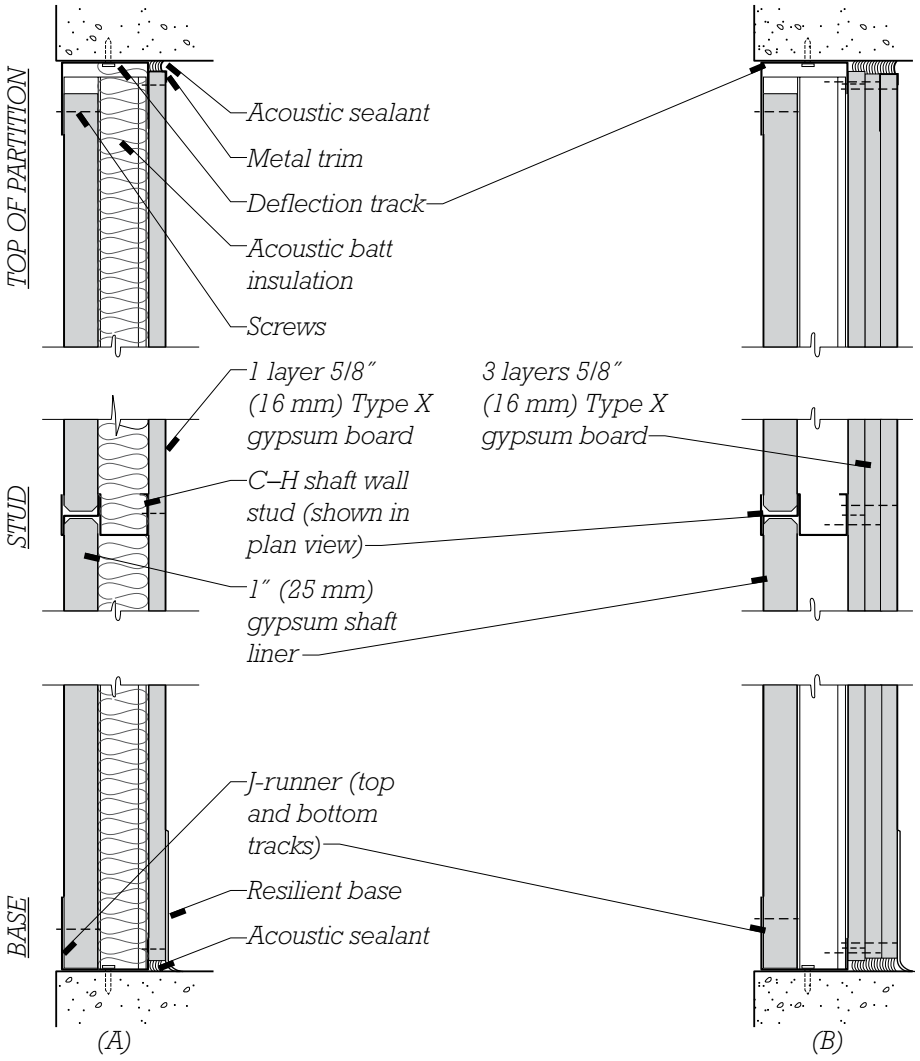


FIGURE 23.32

Two gypsum shaft walls, framed with metal J-runners and C–H studs. The H-shaped portion of the stud holds the shaft liner panel, while the C-shaped portion accepts the screws used to attach the finish board layers. Partition (*A*) achieves a 1-hour fire resistance rating, and partition (*B*) a 3-hour rating. Both have acoustic ratings in the range of STC 45 to 50. Depths of framing members range from 2½ to 6 inches (64 to 152 mm).

Masonry Partitions

A century or more ago, interior partitions were often made of common brick masonry plastered on both sides. These had excellent acoustic properties and fire resistance ratings but were labor intensive and heavy. Partition systems of hollow clay tile and hollow gypsum tile (Figure 23.33) were developed to meet these objections and continued to be used extensively until the 1950s. Both have now become obsolete in North America, replaced by plaster, gypsum board, and concrete masonry, although they are still frequently encountered in the restoration of older buildings.

Concrete masonry partitions may be plastered or faced with gypsum board but are more often left exposed, either painted or unpainted. Lightweight aggregate may be used to reduce the dead weight of the masonry units. Decorative concrete masonry units, as described in Chapter 9, may also be used. Electrical wiring is more difficult to conceal in concrete masonry partitions; the electrician and the mason must coordinate their work, or the wiring must be mounted on the surface of the wall after the mason has finished.

Glazed structural clay tiles make very durable partitions, especially in areas with heavy wear, moisture problems, or strict sanitation requirements (Figure 23.34). The ceramic glazes are nonfading and virtually indestructible.

Wall and Partition Facings

The vast majority of gypsum board partitions are finished with several coats of paint. For more information about coating materials, see the Chapter 6 sidebar, "Paints and Coatings."

Ceramic tile facings are often added to walls for reasons of appearance, durability, sanitation, or moisture resistance. In a *thickset* or *mortar bed* application, tile is applied to a base of portland cement mortar (Figure 23.35).

Lower-cost tile wall facings eliminate the mortar base and are *thin-set* onto *tile backing boards*, also called *backer boards*, most frequently made of fiber-reinforced lightweight cement or glass-mat-faced water-resistant gypsum board, similar to the floor tile

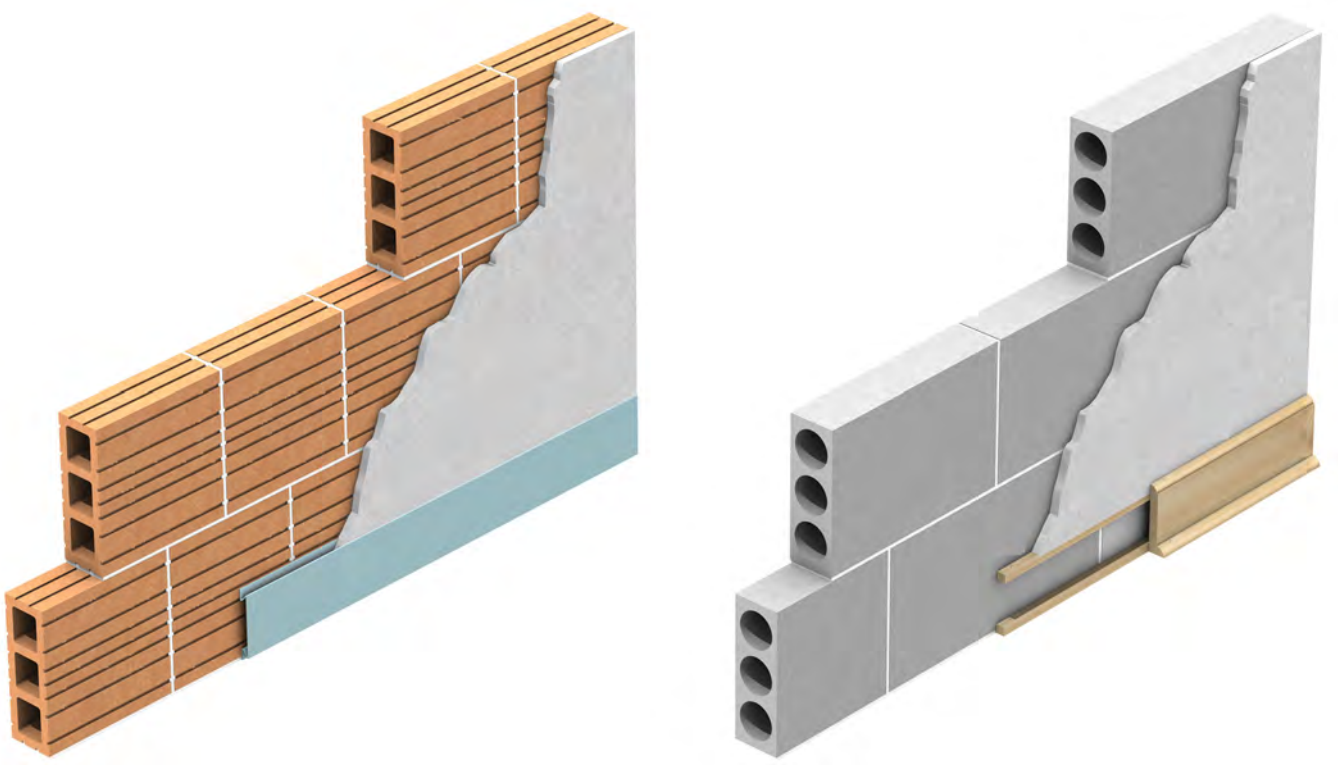


Figure 23.33
Traditional masonry partition systems found in older buildings: hollow clay tiles and plaster (*left*) and gypsum tiles and plaster (*right*).

FIGURE 23.34
A glazed structural clay tile partition installation. The floor is finished with glazed ceramic tiles. *(Courtesy of Stark Ceramics, Inc.)*

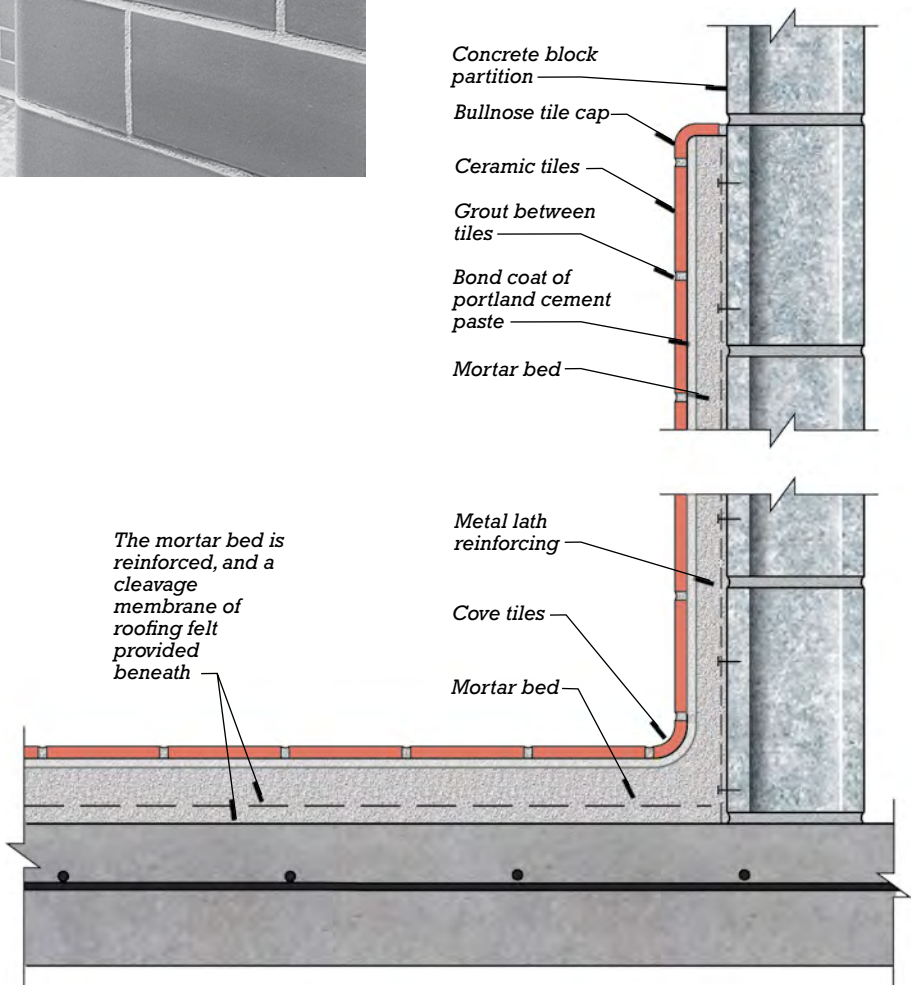


FIGURE 23.35
Sample details of a thickset ceramic tile installation. Thickset applications are used where the face of the partition or the surface of the floor is cracked, coated, rough, unstable, or so uneven as to make it unsuitable for direct bonding of tile using thin-set methods. Depending on the quality of the substrate, metal reinforcing of the portland cement mortar base may or may not be required, and the mortar base may or may not be isolated from the substrate with a layer of felt paper acting as a slip sheet. Thickset mortar beds for wall tiling are typically ¾ to 1 inch (19 to 25 mm) thick, while those for floors are typically 1¼ to 2 inches (32 to 50 mm) thick.

assembly illustrated in Figure 24.27. Cement backer board is the more water resistant, but is more difficult to cut and handle than lighter-weight gypsum backer board.

Tiles are bonded to the backer board with a variety of compounds, the most common of which are dry-set mortar, latex/polymer modified portland cement mortar, and organic adhesive. *Dry-set mortar* is a mix of cement, fine sand, and water retention compounds that allow the thin mortar layer to cure properly. *Latex/polymer modified portland cement mortar* is similar to dry-set mortar, but with additives that improve the cured mortar's freeze-thaw resistance, flexibility, and adhesion. *Organic adhesives* are various synthetic polymer adhesives used for light-duty applications. After the tile bond has fully set, a cementitious *grout* of any desired color is wiped into the tile joints with a rubber-faced trowel. Thin-set compounds and grouts formulated with epoxies or furan resins (colorless, highly volatile solvents distilled from wood) may be used for tiling applications where greater strength, impact resistance, or chemical resistance is required.

In showers, steam rooms, and other wet locations, a *tile waterproofing membrane* is added to the assembly to prevent water from seeping through the tile and into the wall behind. Either liquid-applied or flexible sheet membranes may be used, usually positioned beneath the mortar bed in a thickset application or over the backer board when tile is thin-set.

Facings of granite, limestone, marble, or slate can be applied over almost any partition type. One method of mounting is shown in Figure 23.36.

Wood wainscoting and paneling are normally applied over gypsum wallboard. This retains the acoustic and fire resistance benefits of the gypsum panels and allows these combustible finishes to be used even in noncombustible buildings. Combustible finishes themselves must also meet the fire and smoke criteria for interior finishes, as discussed in Chapter 22.

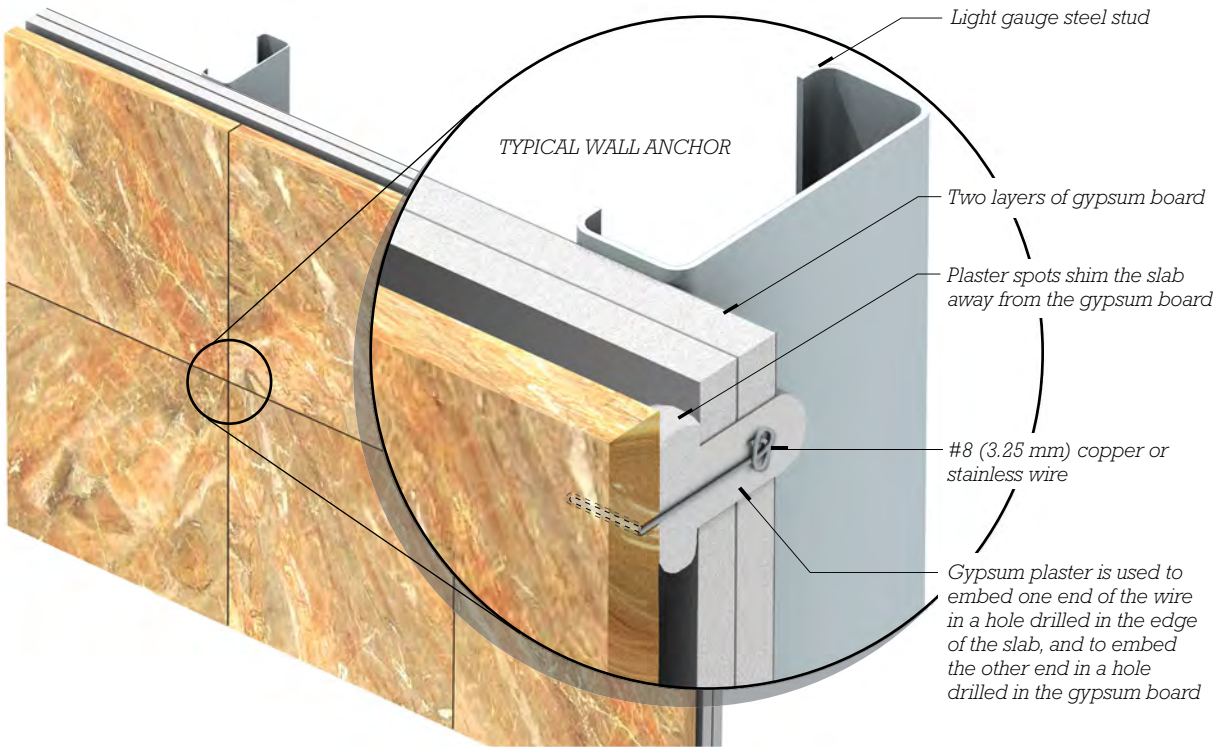


FIGURE 23.36
Attaching a stone facing over a backup of gypsum board and steel studs.

FIGURE 23.37
Interior walls and ceilings of the St. Ignatius Chapel, by the architect Steven Holl, are finished with gypsum plaster over metal lath. A gentle surface texture expresses the hand-crafted origin of the material. The surfaces were left unpainted. *(Photo by Joseph Iano.)*

MasterFormat Sections for Interior Walls and Partitions

04 21 00	**CLAY UNIT MASONRY**
04 22 00	**CONCRETE UNIT MASONRY**
04 42 00	**WOOD PANELING**
09 21 00	**PLASTER AND GYPSUM BOARD ASSEMBLIES**
09 22 00	**SUPPORTS FOR PLASTER AND GYPSUM BOARD**
09 22 13	Metal Furring
09 22 16	Non-Structural Metal Framing
09 22 36.13	Gypsum Lath
09 22 36.33	Metal Lath
09 22 39	Veneer Plaster Base
09 28 00	**BACKING BOARDS AND UNDERLAYMENTS**
09 29 00	**GYPSUM BOARD**
09 30 00	**TILING**
09 75 00	**STONE FACING**
09 81 00	**ACOUSTIC INSULATION**
09 91 00	**PAINTING**
09 91 23	Interior Painting
09 94 00	**DECORATIVE FINISHING**
09 94 13	Textured Finishing
10 22 00	**PARTITIONS**
10 22 19	Demountable Partitions

Key Terms

fire wall
fire barrier
fire partition
fire area
shaft wall
smoke barrier
smoke partition
light gauge steel stud
light gauge steel track, light gauge steel runner
deflection track, slip track
furring strip
Z-furring
hat channel
plaster
lath
wattle and daub
gypsum
calcined gypsum
plaster of Paris
synthetic gypsum
flue-gas desulfurization gypsum (FGD gypsum)
gypsum plaster
base-coat plaster
finish-coat plaster
ready-mixed base-coat plaster
neat base-coat plaster
lime
ready-mixed finish plaster
gauging plaster
portland cement–lime plaster, portland cement plaster, stucco
hawk
trowel
darby
keying
lather
expanded metal lath
self-drilling, self-tapping screw [single term]
lathing nail
gypsum lath
veneer plaster base, gypsum veneer base
lathing trim accessories
control joint
ground
scratch coat
brown coat
plaster screed
finish coat
veneer plaster
acoustic batt insulation
casting
running
cast plaster ornament
run plaster ornament
gypsum board, gypsum wallboard, plasterboard, drywall
Type X gypsum board
moisture-resistant gypsum board
abuse-resistant gypsum board
impact-resistant gypsum board
mold-resistant gypsum board
shaft liner
tapered edge
nail popping
joint compound
drying-type joint compound
setting compound
lightweight joint compound
dustless joint compound, dust control joint compound
finish level
fire-taping
skim coat
demountable partition system
gypsum shaft wall
J-runner
C–H stud
glazed structural clay tile
ceramic tile
thickset tile application, mortar bed tile application
thin-set tile application
tile backing board, backer board
dry-set mortar
latex/polymer modified portland cement mortar
organic adhesive
grout
tile waterproofing membrane

Review Questions

1. What are the major types of interior walls and partitions in a larger building, such as a hospital, classroom building, apartment building, or office building? How do these types differ from one another?

2. Why is gypsum used so much in interior finishes?

3. Name the coats of plaster used over expanded metal lath and explain the role of each.

4. Under what circumstances would you specify the use of portland cement plaster? Metal lath and gypsum plaster? Veneer plaster?

5. Describe step-by-step how the joints between sheets of gypsum board are made invisible.

Exercises

1. Determine the construction of a number of partitions in the places where you live and work. What materials are used? What accessories? Why were these chosen for their particular situations? Sketch a detail of each partition.

2. Sketch typical details for either a plaster or gypsum board partition, working from memory as much as possible. Draw the parts in the same order in which they are assembled on the construction site. Label all the parts.

3. What type of gypsum wall finish system would you specify for a major art museum? For a low-cost rental office building? Outline a complete specification of wall and partition construction for a building you are currently working on.

Selected References

Gypsum Association. *GA-600 Fire Resistance Design Manual*. Washington, DC, updated regularly.

Fire resistance ratings and STCs are given in this booklet for a large number of wall and ceiling assemblies that use either gypsum plaster or gypsum board. This and many other useful resources are also available for free download from the Gypsum Association's website.

Pegg, Brian, and W. D. Stagg. *Plastering: An Encyclopedia* (4th ed.). Oxford, Blackwell Publishing/New York, Crown Publishers, 2007.

Techniques of ornamental plastering are covered in complete detail in this 276-page reference work.

Portland Cement Association. *Portland Cement Plaster (Stucco) Manual*. Skokie, IL, 2003.

A complete, illustrated guide to stucco.

Tile Council of North America. *TCNA Handbook for Ceramic, Glass, and Stone Tile Installation*. Anderson, SC, updated regularly.

This is the definitive standard for ceramic tile installation materials and methods. More than 100 methods of installation for floors and walls, both interior and exterior, are illustrated and specified. Guidelines for selecting appropriate installation methods based on project requirements are also included.

USG Company. *Gypsum Construction Handbook*. Chicago, revised regularly.

This manual represents manufacturers' literature at its best—close to 600 well-illustrated pages crammed with every important fact about gypsum wallboard, gypsum plaster, and associated products. Available for purchase or as a free download from the USG website.

USG Company. *SA100: Fire-Resistant Assemblies*. Chicago, revised regularly.

Though limited to this company's products, this brochure provides an extensive and easy-to-use listing of fire-rated and acoustically rated wall and ceiling assemblies. Along with many other useful technical documents, it is available for free download from the USG website.

Websites

ClarkDietrich (metal framing): www.clarkdietrich.com

Georgia-Pacific: www.buildgp.com/georgia-pacific-gypsum

Gypsum Association: www.gypsum.org

National Gypsum: www.nationalgypsum.com

PCA (Portland Cement Association): www.cement.org

USG (United States Gypsum Company): www.usg.com

TO CONCOURSE

24

Finish Ceilings and Floors

- **Finish Ceilings**
  - Ceiling Acoustics
- **Types of Ceilings**
  - Exposed Structural and Mechanical Components
  - Tightly Attached Ceilings
  - Suspended Ceilings
  - Interstitial Ceilings

Sustainability and Finish Ceilings and Floors

- **Finish Flooring**
  - Reducing Noise Transmission through Floors
  - Resistance to Fire
  - Slip Resistance
  - Electrical Resistivity
  - Underfloor Services
  - Flooring Thickness
- **Types of Finish Flooring Materials**
  - Hard Flooring Materials
  - Wood and Bamboo
  - Resilient Flooring
  - Carpet
  - Fluid-Applied Flooring

The vaulted ceiling of Seattle's Great Hall, Union Station, constructed in 1911 and designed by architect Daniel J. Patterson, includes sandstone, terra cotta, and plaster. *(Photo by Joseph Iano.)*

As the ceilings and finish floors are being installed, the construction of a building is drawing to a close. The components of the mechanical and electrical systems that remain exposed are either finished or concealed, intersections of interior surfaces are neatly trimmed, and painters work their magic to reveal for the first time the interior character of the building. The architect, engineers, and municipal building officials make their last inspections, and, following last-minute corrections of minor defects, the contractor turns the building over to its owner.

Finish Ceilings

The ceiling surface is an important functional component of a room. It helps control the diffusion of light and sound around the room. It may play a role in preventing the passage of sound vertically between the rooms above and below, and horizontally between rooms on either side of a partition. It is may be designed to resist the passage of fire and must itself be appropriately noncombustible. Frequently, it is called upon to assist in the distribution of conditioned air, artificial light, and electrical energy. In many buildings, it must accommodate sprinkler heads for fire suppression and loudspeakers for intercommunication systems. And the ceiling's color, texture, pattern, and shape are prominent in the overall visual character of the room.

A ceiling can be a simple, level plane, a series of sloping planes that give a sense of the roof above, a luminous surface, a richly coffered ornamental ceiling, or even a frescoed plaster vault such as Michelangelo's famous ceiling in the Sistine Chapel in Rome. The possibilities are endless.

Ceiling Acoustics

The sound absorption performance of a ceiling material is measured as its Sound Absorption Average (SAA) or Noise Reduction Coefficient (NRC), as explained in detail in Chapter 22. SAA or NRC ratings for acoustical ceiling materials range from 0.50 to 0.90, compared to ratings below 0.10 for plaster and conventional gypsum board. This makes acoustical ceilings valuable for reducing noise levels in office spaces, restaurants, retail stores, and other noisy environments.

The lightweight, porous materials that produce high SAA or NRC

ratings allow most sound energy to pass through the material. In other words, a ceiling made of porous materials will not furnish very good acoustic privacy between adjacent rooms unless a suitable full-height wall separates the rooms and blocks the passage of sound through ceiling plenum. The ability of a ceiling system to reduce sound transmission from one room to another when the rooms share the same plenum space is measured by its *Ceiling Attenuation Class* (*CAC*). CAC is measured in decibels, with higher values representing greater reductions in sound transmission. Dense, nonporous ceiling materials tend to have higher CACs than lighter, more porous materials. For closed offices with shared ceiling plenums, a ceiling system with a CAC of at least 35 to 40 is recommended.

A third measure of ceiling acoustical performance is *Articulation Class* (*AC*). Like SAA or NRC, AC is a measure of sound absorption. However, AC is intended specifically to measure a ceiling system's contribution to speech clarity and privacy in a typical open office environment. It measures a ceiling's absorption of sound over a 60-inch (1500-mm)-high partition at frequencies ranging from 500 to 4000 Hz, those particularly critical to normal speech. Higher AC values represent greater acoustical clarity and privacy, with minimum recommended values falling in the range of 170 to 200.

Where both noise reduction within a space and sound attenuation between spaces are required simultaneously, composite ceiling panels with an absorbent material laminated to a dense substrate may be used; these have high values for both noise reduction (SAA, NRC, or AC) and sound attenuation (CAC). A similar result can be achieved by mounting acoustically absorbent tiles on a suspended ceiling of plaster or gypsum board.

Types of Ceilings

Exposed Structural and Mechanical Components

In many buildings, it makes sense to omit finished ceiling surfaces altogether and simply expose the structural and mechanical components of the floor or roof above (Figure 24.1). In industrial and agricultural buildings, where appearance is not of prime importance, this approach offers the advantages of economy and ease of access for maintenance. Many types of floor and roof structures are inherently attractive if left exposed, such as heavy timber beams and decking, concrete waffle slabs, and steel trusses. Other types of structures, such as concrete flat plates and precast concrete planks, have little visual interest, but their undersurfaces can be painted and left exposed as finished ceilings in apartment

Figure 24.1
HVAC system ductwork, electrical conduit, lighting fixtures, skylights, curtain area dividers, and athletic equipment are exposed in a ceiling structure of painted open-web steel joists and corrugated steel decking. *(Weinstein A\|U, architect. Photo by Joseph Iano.)*

Figure 24.2
Spraying a textured finish onto the underside of a concrete slab in a residential building, where there are no pipes, ducts, or wires to be concealed below the plane of the floor structure. *(Courtesy of United States Gypsum Company.)*

buildings and hotels, which have little need for services at the ceiling. This saves money and reduces the overall height of the building. In some buildings, the structural and mechanical elements at the ceiling, if carefully designed, installed, and painted, can create a powerful aesthetic of their own.

Exposing structural and mechanical components rather than covering them with a finished ceiling does not always save money. Mechanical and structural work is not normally done in a precise, attractive fashion because it is not usually expected to be visible, and it is less expensive for workers to take only as much care in installation as is required for satisfactory functional performance. To achieve perfectly straight, neatly sealed ductwork that is free of dents, steel decks without rust and weld spatter, and square, well-organized runs of electrical conduit and plumbing, the drawings and specifications for the project must tell exactly the results that are expected, and a higher labor cost must be anticipated.

Tightly Attached Ceilings

Ceilings of almost any material can be attached directly to the underside of the structure above. Commonplace examples include gypsum board or plaster mounted directly to the underside of wood or steel joists and rafters, acoustical tile adhered to the underside of a concrete deck, and textured, acoustic materials spray-applied to the underside of concrete slabs or corrugated metal decking (Figure 24.2). When finish ceilings are in direct contact with the structure above, special finishing arrangements must be worked out for any beams and girders that protrude through the plane of the ceiling, and for ducts, conduits, pipes, and sprinkler heads if these elements are located below the ceiling.

Suspended Ceilings

A ceiling that is suspended on wires some distance below the floor or roof structure can hang level and flat despite varying sizes of girders, beams, joists, and slabs above, and even under a roof structure that slopes toward roof drains. Ducts, pipes, and conduits can run freely in the *plenum* space between the ceiling and the structure above. Lighting fixtures, sprinkler heads, loudspeakers, and fire detection devices may be recessed into the ceiling. Such a ceiling can also—at additional cost—serve as a *membrane ceiling*, or *membrane fire protection*, for the floor or roof structure above, eliminating much of the need for fussy individual fireproofing of steel joists or imparting a higher fire resistance rating to wood or precast concrete structures. For these reasons, *suspended ceilings* are a popular and economical feature in many types of buildings, especially office and retail structures.

Suspended ceilings can be made of almost any material; the ones most widely used are gypsum board, plaster, and various proprietary panels and tiles composed of incombustible fibers or other material. Each of these is supported on its own system of small steel framing members that hang from the structure on heavy steel wires.

Suspended Gypsum Board and Plaster Ceilings

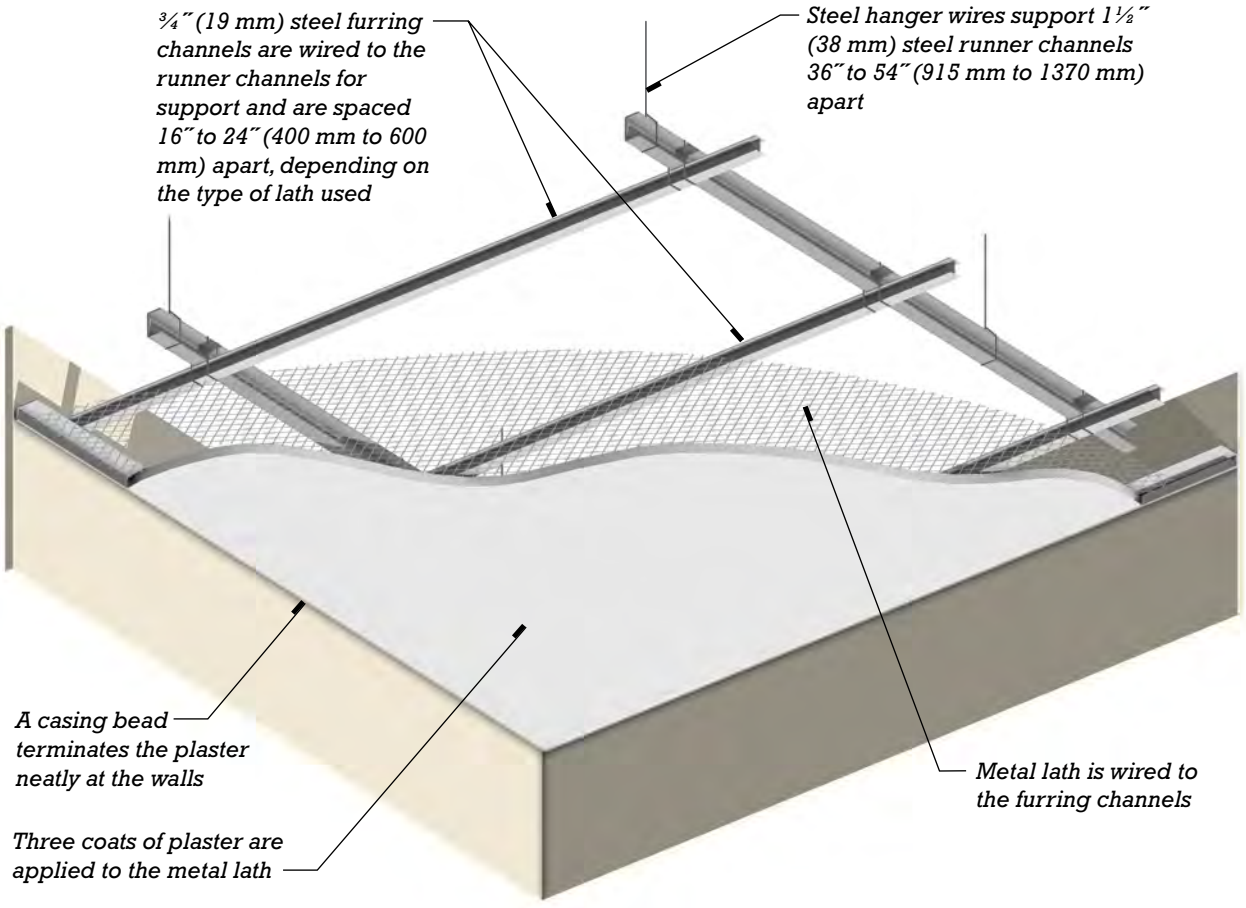
Suspended plaster ceilings, assembled from steel *hanger wire* and cold-rolled channels, have been in use for many decades. Typical details are shown in Figure 24.3. Although most suspended plaster ceilings are flat, lathers are capable of constructing ceilings that are richly sculpted, ranging from configurations resembling highly ornamented Greek or Roman coffered ceilings to nearly any form that the contemporary designer can generate. This capability is especially useful in auditoriums, theaters, lobbies of public buildings, and other uniquely shaped rooms.

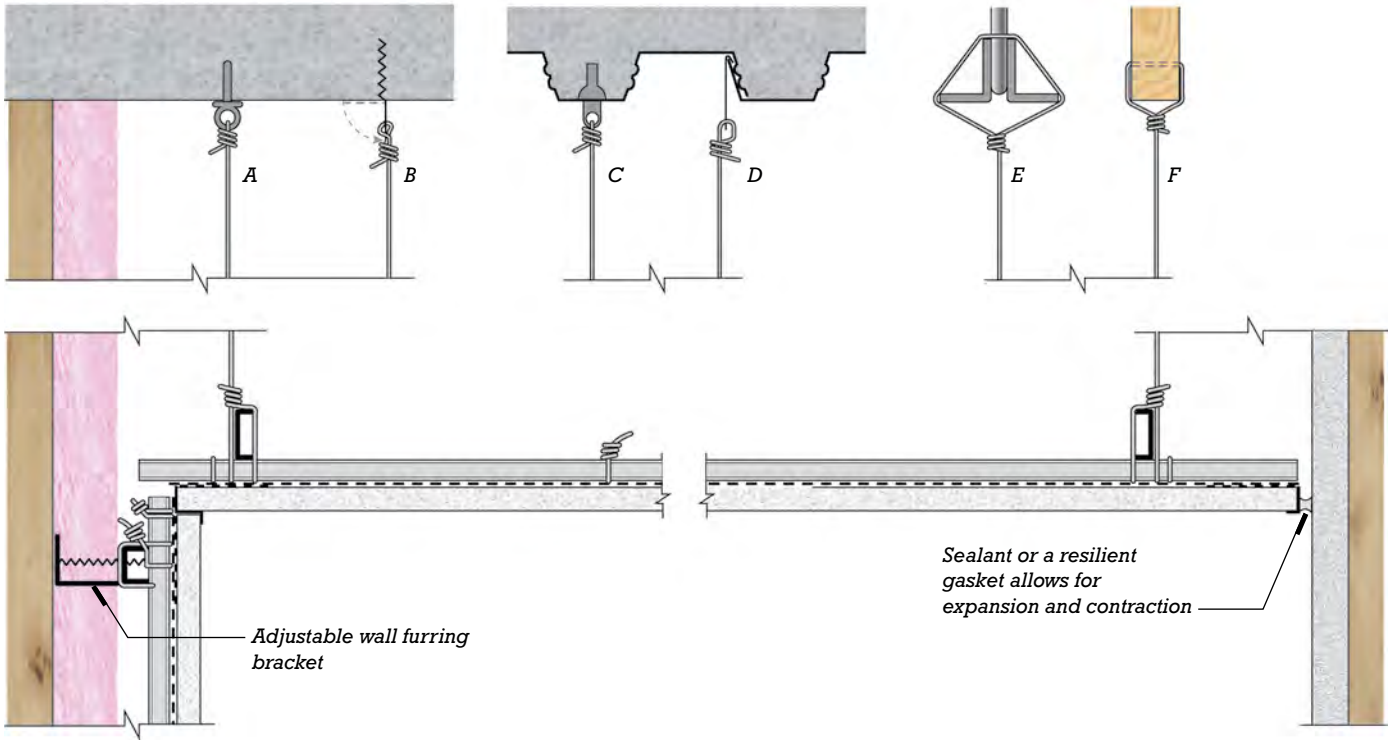
Gypsum board suspended ceilings may be screwed to the same type of suspension system as shown in Figure 24.3 for plaster, to light gauge steel framing made up of stud or joist members, or to grid systems similar to those shown in the next section for suspended acoustical ceilings. Special components have also been developed that make it easy to suspend more complex shapes, such as cylindrical vaults, undulating surfaces, and deep coffers.

Perforated gypsum panels, manufactured with attractively arranged patterns of small holes, are used in gypsum board ceilings where enhanced acoustic performance is required. Panels are mounted to special suspension systems that eliminate the need for normal taping and finishing. With the addition of a layer of acoustic insulation over the top of the panels, acoustic ratings comparable to those of suspended acoustical ceilings, discussed in the next section, are possible.

FIGURE 24.3

A suspended metal lath-and-plaster ceiling. At the top of the page is a cutaway isometric drawing, viewed from below. Across the center of the page are hanger wire support details: (*A*) A pin is powder-driven into a concrete structure. (*B*) A corrugated sheet metal tab with a hole punched in it is nailed to the formwork before the concrete is poured. When the formwork is stripped, the tab bends down and the hanger wire is threaded through the hole. (*C*) A sharp, dagger-like tab of sheet metal is driven through the corrugated metal decking before the concrete topping is poured. (*D*) A sheet metal hook is hung onto the lap joints in the metal decking. (*E*) The hanger wire is wrapped around the lower chord of an open-web steel joist. (*F*) The hanger wire is passed through a hole drilled near the bottom of a wood joist. At the bottom of the page is a section through a furred plaster wall and a suspended plaster ceiling.


¾″ (19 mm) steel furring channels are wired to the runner channels for support and are spaced 16″ to 24″ (400 mm to 600 mm) apart, depending on the type of lath used
Steel hanger wires support 1½″ (38 mm) steel runner channels 36″ to 54″ (915 mm to 1370 mm) apart
A casing bead terminates the plaster neatly at the walls
Three coats of plaster are applied to the metal lath
Metal lath is wired to the furring channels


A
B
C
D
E
F
Adjustable wall furring bracket
Sealant or a resilient gasket allows for expansion and contraction

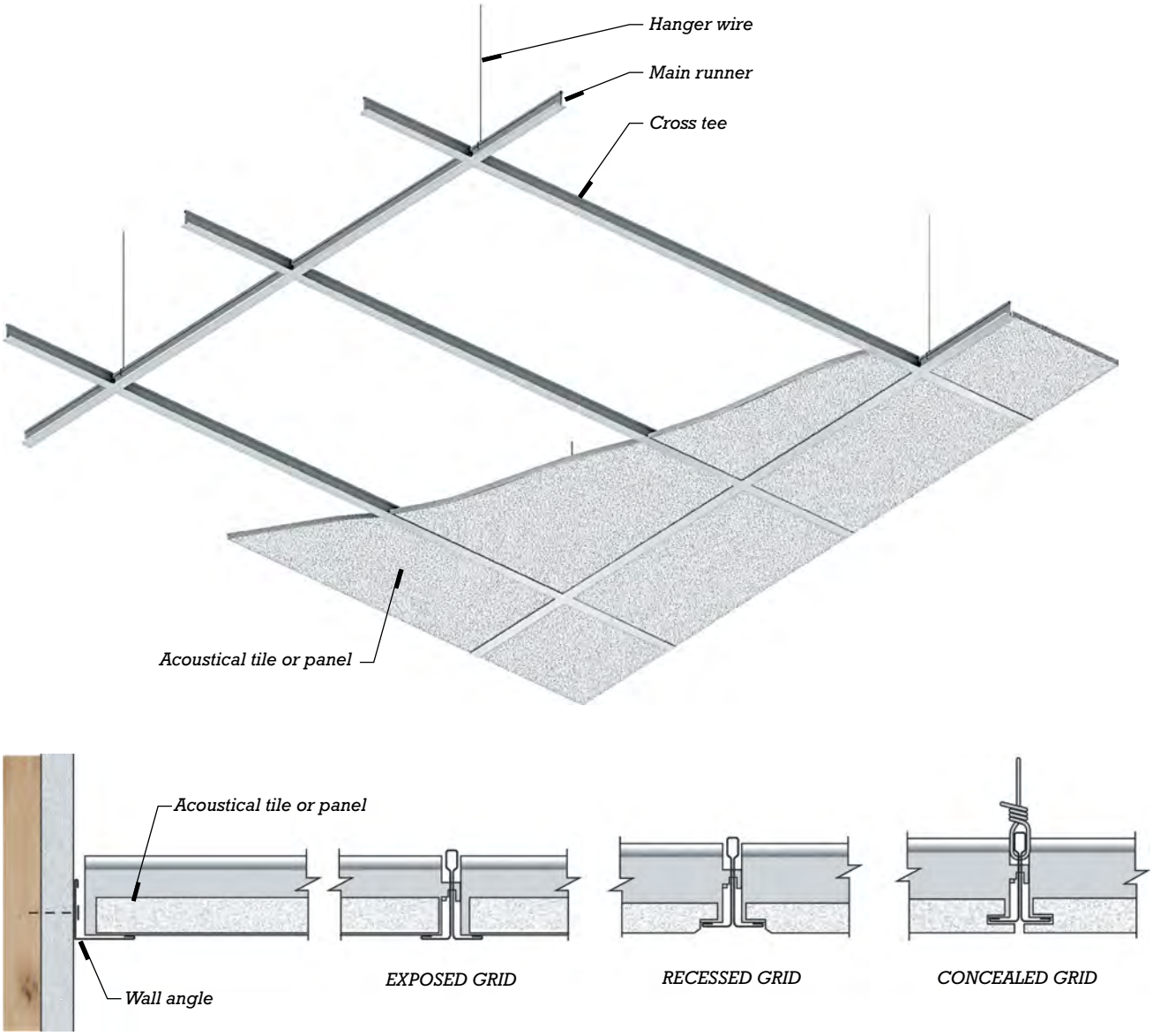


FIGURE 24.4
Acoustical ceilings are supported on suspended grids of tees formed from sheet metal. At the top of the figure is a cutaway view looking up at an acoustical ceiling of lay-in panels. Below are sections illustrating how the grid may be exposed, recessed, or concealed for different appearances.

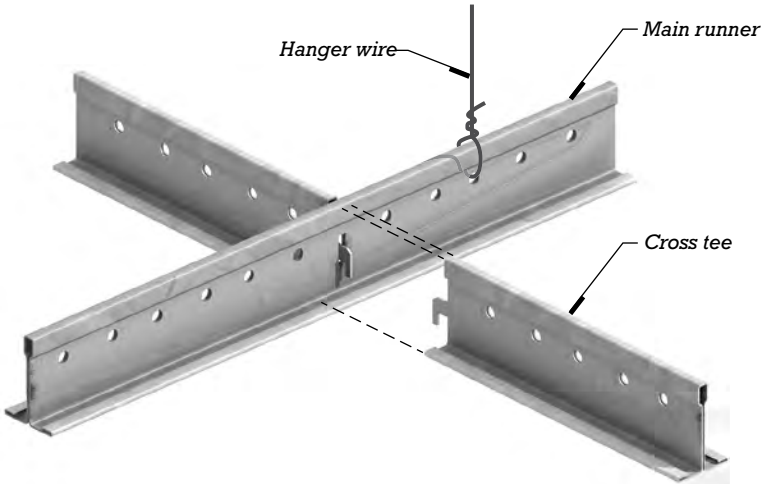


FIGURE 24.5
The grid for an acoustical ceiling is assembled with a simple interlocking joint.

Suspended Acoustical Ceilings

Ceilings made from fibrous materials in the form of lightweight tiles or panels are customarily referred to as *acoustical ceilings* because most of them are absorptive of sound energy, unlike plaster and gypsum board, which are more reflective of sound. They are also often less costly than either plaster or gypsum board ceilings.

The most economical acoustical ceiling systems consist of *lay-in panels* that are supported by an *exposed grid* (Figures 24.4 and 24.5). Any panel in the ceiling can be easily lifted and removed for access to services in the plenum space. For a neater appearance, a *concealed grid* system may be used. Concealed grid systems require special panels where plenum access is needed. For curved ceilings, curvilinear grid systems and flexible tiles are used to create ceilings that warp along one or both axes of the ceiling plane. Suspended acoustical ceilings are available in hundreds of different designs, a few of which are illustrated in Figures 24.6 through 24.8.

FIGURE 24.6
A concealed suspended grid system with acoustical panels with a finely scored surface pattern. *(Courtesy of Armstrong World Industries.)*

FIGURE 24.7
HVAC diffusers and suspended lighting fixtures are carefully arranged within the grid of this suspended acoustical tile ceiling. Fire sprinklers, a smoke detector, and a fire annunciator can also be seen, mounted flush to the underside of the ceiling.
(Photo by Joseph Iano.)

Interactive Exercise

FIGURE 24.8
A seemingly endless variety of acoustical ceiling panel styles and textures are available. *(Courtesy of Armstrong World Industries.)*

Economy has worked so great a change in our dwellings, that their ceilings are, of late years, little more than miserable naked surfaces of plaster. [A discussion of ceiling design will] possess little interest in the eye of speculating builders of the wretched houses erected about the suburbs of the metropolis, and let to unsuspecting tenants at rents usually about three times their actual value. To the student it is more important, inasmuch as a well-designed ceiling is one of the most pleasing features of a room.

—Joseph Gwilt, *An Encyclopædia of Architecture*, 1842

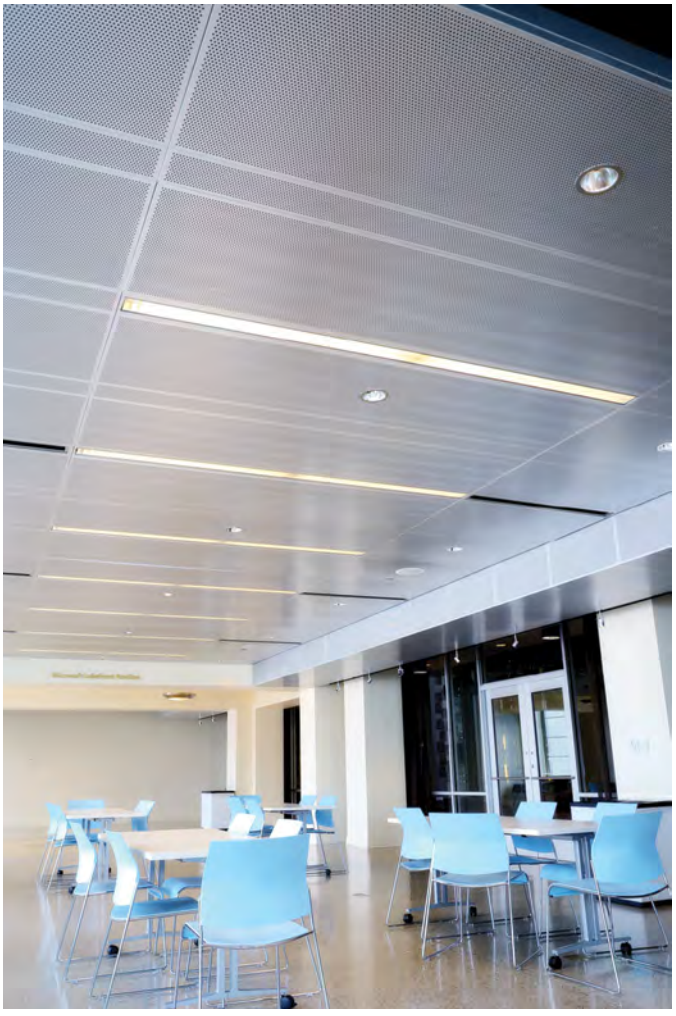


FIGURE 24.9
An *integrated ceiling system* incorporates lighting fixtures and HVAC diffusers into the grid and panel system itself, resulting in a more unified appearance. The acoustical panels are perforated aluminum. A ceiling mounted speaker and concealed fire sprinkler also appear in this image. In the case of fire, the sprinkler head descends far enough through the plane of the ceiling so that the water spray is properly distributed. *(Photo by Joseph Iano.)*

Other Suspended Ceiling Materials

Almost any material can be incorporated into a suspended ceiling system. *Metal panel ceilings* are made from sheet metal suspended in a manner similar to that for acoustic panels (Figures 24.9 and 24.10). *Linear metal ceilings* are made from longer metal strips suspended on a concealed grid system (Figure 24.11). The metal sheets may be solid or perforated, and formed flat, stamped with intricate patterns, or curved, depending on aesthetic and acoustic requirements. Due to its ease of formability and light weight, aluminum is the metal most commonly used.

Suspended wood ceilings, made from solid wood or wood veneered over a variety of substrates, are produced in both panel and linear forms, similar to those of metal (Figure 24.12). Textile ceilings may be made from *fabric-wrapped ceiling panels*, consisting of natural or synthetic fabrics mounted over acoustic panels. Larger, seamless textile ceilings are constructed as *stretched-fabric ceiling systems*, in which a synthetic fabric is stretched across a special mounting system with acoustic insulation behind the fabric. Wherever flammable materials are used in ceilings, these materials must meet the fire criteria requirements discussed in Chapter 22.

With the advent of three-dimensional modeling and computer-driven fabrication techniques, the ability to produce economical yet unique ceiling panel forms continues to grow, further expanding the range of possibilities in suspended ceiling types and designs.

FIGURE 24.10
Trapezoidal panels in a curved, stepped, metal panel ceiling. Air distribution, recessed lighting, and sprinklers are neatly integrated into the ceiling system. *(Photo by Joseph Iano.)*

FIGURE 24.11
A mirror-finish linear metal suspended ceiling, with an exposed steel space truss structure beyond. *(Architect: DeWinter and Associates. Courtesy of Alcan Building Products, division of Alcan Aluminum Corporation.)*

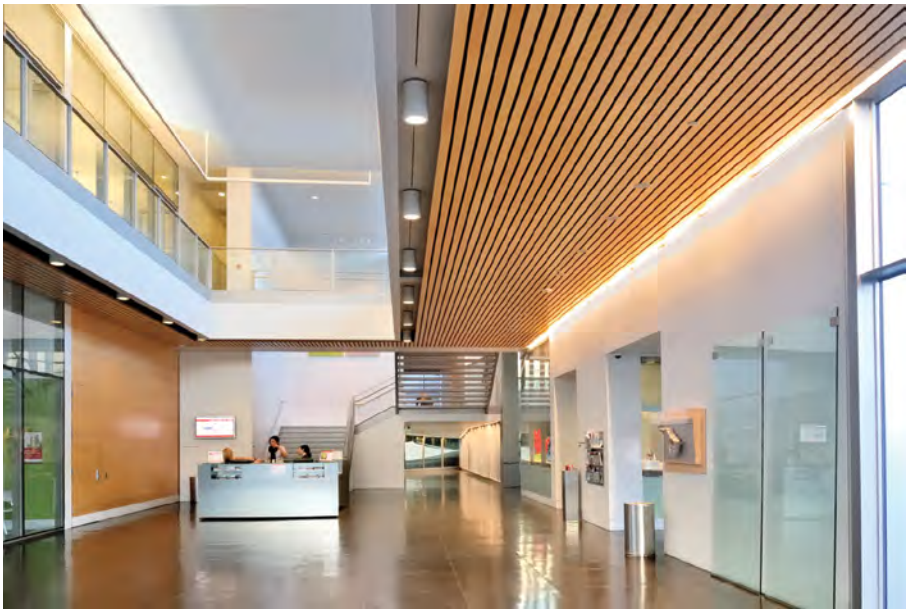
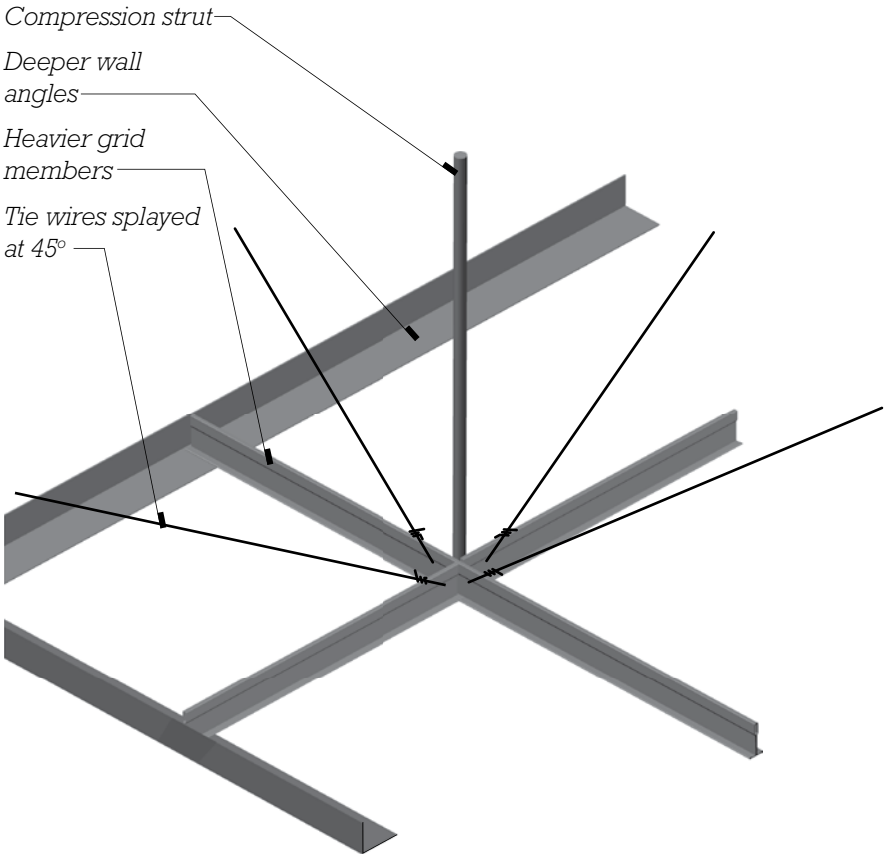


FIGURE 24.12
A linear wood ceiling defines the main circulation spine through a museum entrance lobby. *(Photo by Joseph Iano.)*



Seismic Protection of Suspended Ceilings

Suspended ceiling systems must not pose a threat to the safety of building occupants in the event of a seismic event. In such an occurrence, the ceiling must not collapse, light fixtures and other ceiling-mounted equipment must not fall, and parts of the ceiling must not drop to the floor and hamper egress from the building. Requirements for protecting suspended ceilings vary with the risk of seismic activity at the building location; the size, shape, and weight of the ceiling; the materials from which the ceiling is made; and the type of facility (hospitals, schools, etc., where survivability from seismic events is especially important, receive higher degrees of protection).

In areas of low seismic risk and where ceilings are lightweight and relatively small in area, no special provisions may be required. In other cases, suspended ceiling systems must be strengthened and braced so that they can survive larger movements and greater forces. This can include stronger suspension wires and grid members, deeper perimeter support at walls, and regularly spaced lateral bracing components within the suspension system. Where lateral support is provided, it must be able to resist not only side-to-side movements of the ceiling system, but up-and-down movements as well (Figure 24.13).

FIGURE 24.13
Lateral force bracing for a suspended acoustical ceiling system. Tie wires, splayed at 45° from the horizontal, provide lateral force resistance. A compression strut, made of lightweight electrical conduit or a light gauge metal stud, prevents the ceiling grid from bouncing up and down. Heavier grid members and stronger connections between the members prevent the grid from buckling or pulling apart. And deeper wall angles prevent the grid ends from sliding off the toes of the angles and falling. Light fixtures and other equipment in the ceiling must also be braced.

Suspended Fire-Resistance Rated Ceilings

Membrane ceilings, designed to contribute to the fire resistance of the roof or floor structure above, may be made of gypsum board, plaster, or lay-in panel and grid systems. These ceilings must be carefully detailed and installed to maintain the continuity of the required fire resistance throughout the extents of the ceiling: Lighting fixtures must be backed up with fire-resistive material, air conditioning grills must be isolated from the ducts that feed them by automatic fire dampers, access panels provided for maintenance of above-ceiling services must themselves meet the same fire resistance rating as the ceiling system, and any other penetrations must be appropriately treated. (For more information about membrane fire-protection ceilings, see Figure 11.69.)

Interstitial Ceilings

Many hospital and laboratory buildings have highly elaborate mechanical and electrical systems, including not just the usual air conditioning ducts, water and waste piping, and electrical and communications wiring, but also such services as fume hood ducting, fuel gas lines, compressed air lines, oxygen piping, chilled water piping, vacuum piping, and chemical waste piping. These ducts and tubes occupy a considerable volume of space in the building, often in an amount that virtually equals the inhabited volume. Furthermore, all these systems require continual maintenance and are subject to frequent change. As a consequence, many laboratory and hospital buildings are designed with *interstitial ceilings*. An interstitial ceiling is suspended at a level that allows workers to travel freely in the plenum space, usually while walking erect, and is structured strongly enough to safely support the weight of the workers and their tools. In effect, the plenum space becomes another floor of the building, slipped in between the other floors, and the overall height of the building must be increased accordingly. Its advantage is that maintenance and updating work on the mechanical and electrical systems of the building can be carried on without interrupting the activities below. Interstitial ceilings are made of gypsum or lightweight concrete and combine the construction details of poured gypsum roof decks and suspended plaster ceilings. Figure 24.14 shows the installation of an interstitial ceiling.

FIGURE 24.14

The final steps in constructing an interstitial ceiling: The ceiling plane consists of gypsum reinforced with hexagonal steel mesh. The final layer of gypsum is being pumped onto the ceiling from the hose near the center of the picture. The wet gypsum is struck off level with the wooden straightedge seen here hanging on the beams and is then troweled to a smooth walking surface. When the gypsum has hardened, installation of the ductwork, piping, and wiring in the interstitial plenum space can begin, with workers using the gypsum ceiling as a walking surface. *(Courtesy of Keystone Steel & Wire Co.)*

Sustainability and Finish Ceilings and Floors

For more information about the sustainability of interior finishes in general, see the Chapter 22 sidebar, "Sustainability and Interior Finishes."

Building and Material Life-Cycle Impacts

- Many ceiling and floor materials manufacturers have instituted recycling programs to reclaim their own products at end of life and ensure that these materials are diverted from the waste stream.
- Some manufacturers are practicing *closed-loop recycling*, in which floor and ceiling products at end of life are reclaimed and recycled back into new floor and ceiling product. For example, one major manufacturer claims to have recycled more than 50 million pounds (23 million kg) of old flooring material into new flooring over a five-year period.
- Carpet tile, which allows easy spot replacement, lessens the need for full carpet replacement when a small area becomes worn or damaged, thus extending the life of the carpet installation and reducing waste.
- A manufacturer EPD reports the following cradle-to-grave impacts per square meter (11 sq ft) for suspended acoustical and wood panel ceiling systems:

	Suspended Acoustical Tile	Suspended Wood Panel
Nonrenewable primary energy consumption	98 MJ (250,000 BTU)	260 MJ (420,000 BTU)
Global warming potential	11 kg (24 lb) CO_2 eq.	31 kg (69 lb) CO_2 eq.
Fresh water consumption	2.5 L (0.66 gal)	140 L (36 gal)

- The following compares EPD cradle-to-grave impacts for 1 square meter (11 sq ft) of industry-average vinyl tile and one manufacturer's commercial carpet tile:

	Vinyl Tile	Carpet Tile
Nonrenewable primary energy consumption	200 MJ (190,000 BTU)	1300 MJ (1.3 million BTU)
Global warming potential	27 kg (59 lb) CO_2 eq.	77 kg (170 lb) CO_2 eq.
Fresh water consumption	(Not reported)	(Not reported)

- Flooring industry trade groups have established third-party certification programs for the life-cycle analysis and sustainability assessment of their flooring products, such as NSF/ANSI 140 for carpeting, NSF/ANSI 332 for resilient flooring, and Green Square/ANSI A138.1 for tile flooring.

Material and Production Attributes

- Flooring and ceiling manufacturers, responding to demand for sustainable products, increasingly offer choices of products with a broad range of sustainable attributes, such as high recycled materials content, rapidly renewable materials content, freedom from chemicals of concern, etc.
- Bamboo, used to make flooring, is harvested in a four-to-six-year cycle, making it a rapidly renewable material.
- Linoleum is made from linseed oil, pine rosin, clay, cork, limestone, and jute. Many of its ingredients are renewable, although the extraction of clay and limestone can cause ecological disruption.

Unhealthful Materials and Emissions

- Vinyl (polyvinyl chloride) is a component of many resilient floor coverings and other interior finish products. It is associated with a range of health and environmental concerns, as discussed in more detail in the Chapter 19 sidebar, "Plastics in Building Construction."
- The Resilient Floor Covering Institute's FloorScore program certifies low-emitting resilient flooring products and the Carpet and Rug Institute's Green Label and Green Label Plus standards do the same for carpet products.
- To minimize formaldehyde emissions, engineered wood and bamboo products can be manufactured with no added urea formaldehyde (NAUF) or certified to a low-emission standard such as CARB 2. (See Chapter 3 for more information about formaldehyde and formaldehyde emissions.)
- Where finish floor and ceiling products are glued in place or are finished with sealers or other coating products, these adhesives and coatings should meet the same standards for low emissions as the floor and ceiling materials themselves.
- Stretch-in installation of sheet carpet and free-lay installation of carpet tile (methods of installation explained later in this chapter) eliminate the need for carpet adhesive.
- Concrete, stone, masonry, ceramic tile, and cementitious mortars and grouts are chemically inert and generally free of emissions.
- For more information about finish materials emissions and impacts on indoor air quality, see Chapter 22.

Responsible Industry Practices and Social Impacts

- Carpet America Recovery Effort (CARE) is an industry-sponsored organization with the mission to increase landfill diversion and recycling of carpet waste. Since 2002, CARE members have diverted over 4.5 billion pounds (2.0 billion kg) of postconsumer carpet from U.S. landfills.

Finish Flooring

Floors have a lot to do with our visual and tactile appreciation of a building. We sense their colors, patterns, and textures, their feel underfoot, and the noises they make in response to footsteps. Floors affect the acoustics of a room, contributing to a noisy or hushed quality depending on whether a hard or soft material is used. Floors also interact in various ways with light. Some floor materials give mirror-like reflections; others give diffuse reflections or none at all. Dark flooring materials absorb more of the light incident upon them and contribute to the creation of a darker room, whereas light materials help create a brighter space and in some cases can even contribute to reduced energy consumption by allowing artificial lighting levels to be lowered.

Floors are also a major functional component of a building. They are its primary wearing surfaces, subject to water, grit, dust, and the abrasive and penetrating actions of feet and furniture. They require more cleaning and maintenance effort than any other component of a building. They must be designed to deal with problems of slip resistance, sanitation, noise reduction between floors of a building, and even electrical conductivity in occupancies such as computer rooms and hospital operating rooms, where the buildup of static electricity can pose a hazard. Also, like other interior finish components, floors must be selected with an eye to combustibility, fire resistance ratings, and the structural loads that they will place on the frame of the building.

Reducing Noise Transmission through Floors

In multistory buildings, it is sometimes necessary to take precautions to reduce the amount of impact noise transmitted through a floor to the room below. This is particularly true of hotels, condominiums, and apartment buildings, where people are sleeping in rooms below the rooms of others who may be awake and moving about. Impact noise is generated by footsteps or machinery and is transmitted as structure-borne sound through the material of the floor to become airborne sound in the room below.

There are several strategies for dealing with impact noise. These may be employed individually or in various combinations. One is to use padded carpeting or cushioned resilient flooring to reduce the amount of impact noise that is generated. A second is to add an *acoustic underlayment*, a layer of resilient material that is not highly conductive of impact noise, beneath the finish flooring. Cellulose fiber panels and nonwoven plastic filament matting are two materials used for this purpose. A third mechanism is to make an airtight ceiling below of a heavy, dense material such as plaster or gypsum board, and to mount this ceiling on resilient clips or on hanger wires with springs. The springs or clips absorb much of the sound energy that would otherwise travel through the structure. For more information about floor-ceiling acoustic isolation, see Chapter 22.

Resistance to Fire

Floor finish materials must also meet building code requirements for resistance to ignition by radiant heat and flame spread, as explained in Chapter 22.

Slip Resistance

The slip resistance of a floor surface may be expressed as the *coefficient of friction* (*COF*) between the floor and some reference material, such as rubber or leather. On a level surface, COF is measured as the force required to pull an object across the floor, divided by the weight of the object. For example, if 10 pounds of force is needed to drag a 50-pound rubber block across a floor, the COF between the block and the floor is 0.20 (10 lb/50 lb = 0.20). A lower COF implies a more slippery surface, and a higher coefficient, a less slippery one. COF may be measured starting with an object at rest, the *static coefficient of friction* (*SCOF*), or after the object has started to slide, the *dynamic coefficient of friction* (*DCOF*). Usually, more force is required to initiate sliding of a stationary object than is required to keep an object sliding once it starts. So, for any combination of materials and conditions, SCOF is typically higher than DCOF.

There is at this time no recognized North American general standard for specifying and measuring the slip resistance of floors in buildings. Accessibility regulations require that the surfaces of accessible routes be stable, firm, and slip-resistant, but do not provide guidance on how to determine slip resistance. The Occupational Health and Safety Administration provides a nonmandatory recommendation of a SCOF of 0.50 or greater for workplace floor surfaces, but does not indicate what test method should be used to determine these values. (COF measurements can vary widely depending on how the testing is performed.)

Two related standards for specifying the slip resistance of flooring materials are ANSI A326.3, applicable for hard surface flooring materials, and ANSI A137.1, a ceramic tile standard that also includes slip resistance criteria. These voluntary standards both specify the same test procedure for measuring slip resistance and provide a recommended minimum DCOF for interior, level floor surfaces of 0.42 when tested in a wet condition. Another voluntary standard, ANSI B101, is intended primarily as a guide for property maintenance and workplace safety. It provides recommendations for minimum COF values to achieve three levels of floor traction, designated as Low, Moderate, or

High. None of these standards have universal applicability, and the relationships between their criteria and the actual risks of pedestrian slip-and-fall accidents are not always clear. As such, guidance for floor slip resistance remains incomplete.

Electrical Resistivity

In areas housing equipment that could be damaged by static electrical discharge, *static control flooring* provides a moderately conductive pathway for the dissipation of electrical charge between occupants and equipment. In this way, sudden, large, damaging discharges are prevented.

Underfloor Services

Floor structures are frequently used for the distribution of electrical and communications wiring, especially in areas that are broad and have few fixed partitions. If the needs for services are minimal and predictable, the most economical horizontal distribution system for wiring in a floor consists of conventional conduits of metal tubing that are embedded in the floor slab or concrete topping. In most commercial buildings, however, greater flexibility is required to accommodate wiring changes that will have to occur during the life of the building. There are several alternative systems for creating this flexibility. In buildings with concrete structural systems, *cellular raceways* may be cast into the floor slabs (Figure 24.15). These are sheet metal ducts that can carry many wires. Working through access boxes that reach from the top of the raceway to the surface of the slab, electricians can add or remove wiring at any time. Electrical and communications outlets can be installed in any of the access boxes.

In steel-framed buildings, *cellular steel decking* provides the same functional advantages as cellular raceways (Figure 24.16). *Poke-through fittings* (Figure 24.17) allow wiring flexibility over time without the need for raceways or cellular decking. Poke-through systems, however, require the electrician to work from the floor below the one on which changes are being made, which can be an inconvenience for the tenants of the lower floor.

Raised access flooring is advantageous in buildings where wiring changes are frequent and unpredictable, such as equipment-intensive offices and dedicated server rooms (Figures 24.18 and 24.19). Raised access flooring has a virtually unlimited capability to meet future wiring needs, and changes in wiring are extremely easy to make. If the access floor is raised high enough, ductwork for air distribution can be run beneath it, possibly eliminating the need for a suspended ceiling. This can be useful in buildings where the structural system is meant to be left exposed as a finish ceiling, or in older buildings with beautiful plaster or wood ceilings. Raised access flooring also works well in older buildings because its pedestal heights can be adjusted to compensate for uneven floor surfaces. Several systems for providing individualized control of air conditioning in large office buildings utilize the space below a raised access floor as a large distribution chamber for conditioned air, with each workstation provided with a small outlet diffuser in the floor surface.

With *undercarpet wiring systems*, electrical power and communications

Figure 24.15
A worker levels a cellular raceway over steel dome formwork for a concrete waffle slab floor structure. The concrete will be poured so that its surface is level with the tops of the access boxes, completely embedding the raceways and allowing each box to be opened merely by removing its metal cover. Electrical and communications outlets can be installed in any access box. The covers of unused access boxes will be concealed beneath vinyl composition floor tiles or carpeting. *(Courtesy of American Electric—Construction Materials Group.)*

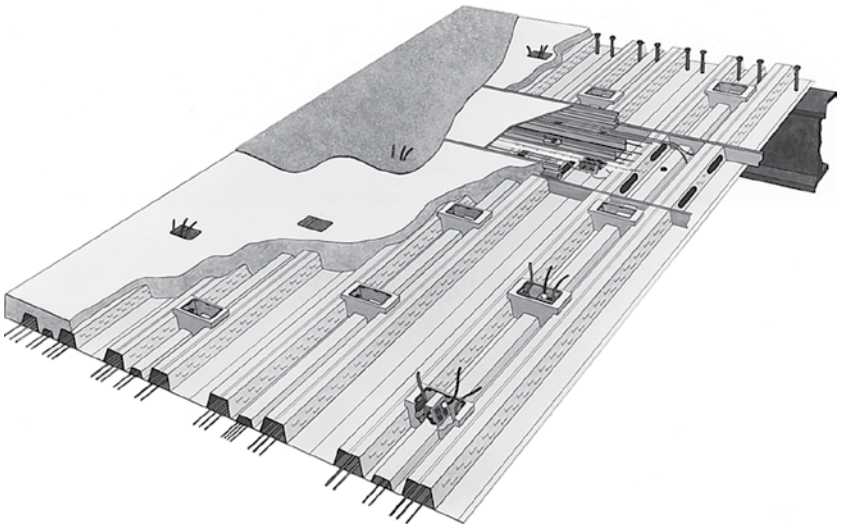
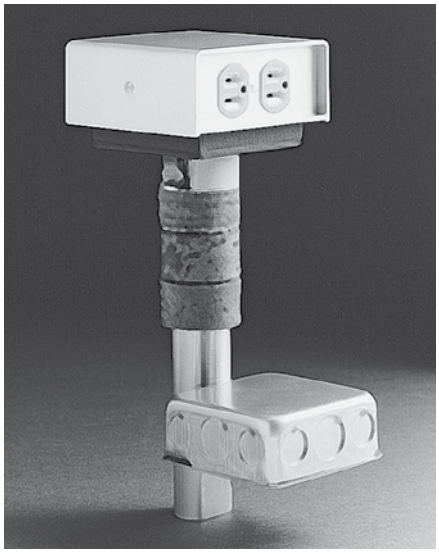


FIGURE 24.16
Cellular steel decking is often used for underfloor electrical and communications wiring. A transverse feeder trench, near the top of the picture, brings the wiring across the floor from the electrical risers to the cells in the deck. Boxes cast into the topping give access to the cells for the installation of electrical outlets. Notice the shear studs on the steel beam at the top of the picture. *(Courtesy of HH Robertson.)*



(*a*)

(*b*)

FIGURE 24.17
(*a*) A poke-through fitting is designed to be installed in a hole drilled through a concrete floor slab. The junction box at the bottom connects to a wiring conduit above the suspended ceiling of the floor below. Wires pass from the junction box through the vertical tube to the outlet above. (*b*) Gaskets act as firestopping to seal the hole through the slab so that fire cannot pass, thus maintaining the fire resistance rating of the floor structure. If a poke-through fitting is removed in a later renovation, a special fire-resistant abandonment plug is installed to seal the hole. *(Courtesy of American Electric—Construction Materials Group.)*

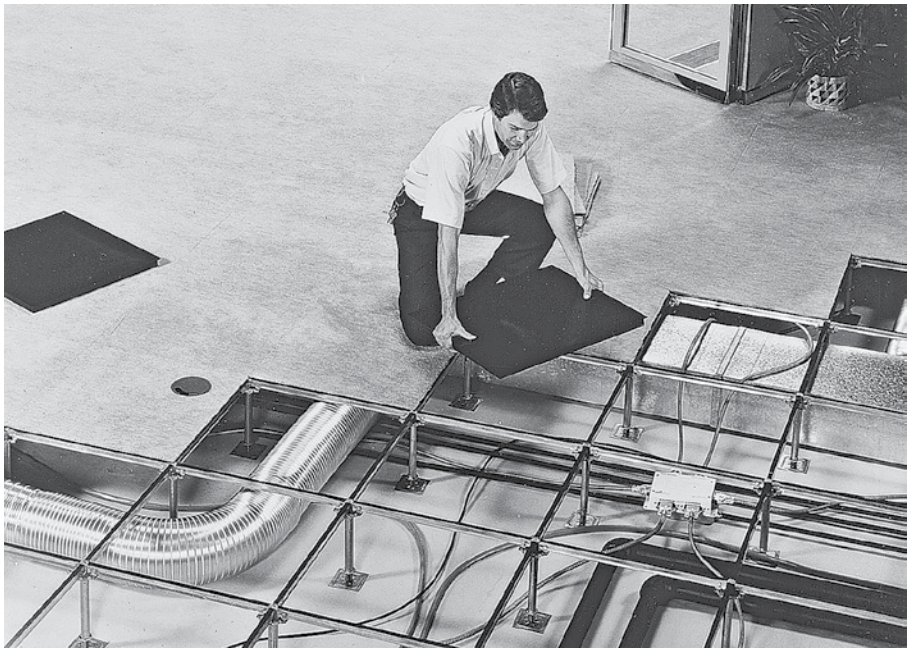


FIGURE 24.18
Raised access flooring provides unlimited capacity for wiring, piping, and ductwork. The space below the flooring can serve as a plenum for air distribution. Changes in any of the underfloor systems are easily made, and wiring outlets can be installed at any point in the floor. *(Courtesy of Tate Architectural Products, Inc.)*

wiring can be delivered within the floor system using flat conductors rather than conventional round wires installed between the finish flooring and the slab below. Undercarpet wiring is especially useful for retrofit projects where the previously discussed systems for delivering in-floor service are less practical (Figure 24.20).

Flooring Thickness

Thicknesses of floor finishes vary from ⅛ inch (3 mm) or less for resilient and fluid-applied flooring to 3 inches (76 mm) or more for brick or stone flooring. Frequently, several different types of flooring are used on different areas of the same floor level of a building. If the differences in thickness of the flooring materials are not great, they can be resolved by using tapered edgings or thresholds at changes of material. Greater differences may be resolved with variations in the thickness of underlayment panels. Or, *self-leveling underlayments*, formulated from gypsum or portland cement, can be poured up to several inches thick over portions of a subfloor to raise the level before application of the finish flooring.

If none of these solutions can satisfactorily resolve floor level differences, the level of the top of the floor deck must be adjusted from one part of the building to the next to bring the finish floor surfaces to the same elevation. In wood framing, level changes can usually be made either using shallower, more closely space joists, notching the ends of the floor joists to lower the subfloor in parts of the building with thicker floor materials, or adding sheets of underlayment material of the proper thickness to areas of thinner flooring. In steel and concrete buildings, slab or topping thicknesses can change, or whole areas of the structure can be raised or lowered by the necessary amount.

The brick floors, because the bricks may be made of diverse forms and of diverse colors by reason of the diversity of the chalks, will be very agreeable and beautiful to the eye. . . . The ceilings are also diversely made, because many take delight to have them of beautiful and well-wrought beams. . . . [T]hese beams ought to be distant one from another one thickness and a half of the beam, because the ceilings appear thus very beautiful to the eye.

—Andrea Palladio, *The Four Books on Architecture*, 1570

FIGURE 24.19
Conditioned air is supplied to this server room through the space below the raised access flooring and is fed upward through perforated floor panels. Air is returned through slots in the suspended ceiling. *(Courtesy of Armstrong World Industries.)*

FIGURE 24.20
The flat conductors of an undercarpet wiring system are ribbons of copper laminated between insulating layers of plastic sheet. These conductors are connected with the splicing tool shown in this photograph and covered with a grounded metallic shield before being taped to the floor. *(Courtesy of Burndy Corporation.)*

Types of Finish Flooring Materials

Hard Flooring Materials

Hard finish flooring materials (concrete, stone, brick, tile, and terrazzo) are often chosen for their resistance to wear and moisture. Being rigid and unyielding, they are not comfortable to stand on for extended periods of time, and they contribute to a "live," noisy acoustic environment. Many of these materials, however, are beautiful in their colors and patterns, durable, and often considered highly desirable by designers and building owners alike.

Concrete

With a lightly textured wood float finish for traction, concrete makes an excellent finish floor for parking garages and many types of agricultural and industrial buildings. With a smooth, hard, steel trowel finish, concrete finds its way into a vast assortment of commercial and institutional buildings, and even into homes and offices. Machine-polished concrete floors can achieve an almost glasslike level of smoothness and sheen. Color can be added with a colorant admixture, a concrete stain, or a couple of coats of floor paint. For industrial floors where hardness and durability are a special concern, *concrete hardeners* that densify the wearing surface of the concrete are added during slab finishing operations.

The chief advantages of concrete as a finish flooring material are its low initial cost and its durability. On the minus side, extremely good workmanship is required to make an acceptable floor finish, and, unless applied as a finish topping very close to the end of construction, even the best concrete surface is likely to sustain some damage and staining during construction.

Stone

Many types of building stone are used as flooring materials, in surface textures ranging from mirror-polished marble and granite to split-face slate and sandstone (Figures 24.21 and 24.22). Installation is a relatively simple but highly skilled procedure of bedding the stone pieces in mortar and filling the joints with grout. Most stone floorings are coated with applications of a clear sealer and are waxed periodically throughout their life to bring out the color and figure of the stone while protecting it from stains.

Figure 24.21
A slate floor in an automobile showroom. *(Photo by Bill Engdahl, Hedrich Blessing Photographers, courtesy of Buckingham-Virginia Slate Corporation.)*

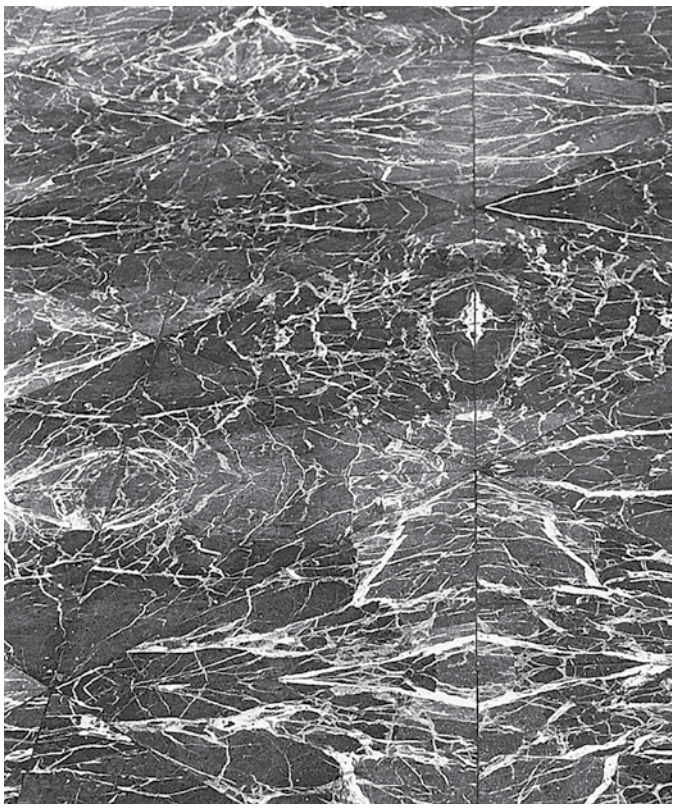


Figure 24.22
Flooring of matched, polished triangles of white-veined red marble gives a kaleidoscopic effect. *(Architect: The Architects Collaborative. Photo by Edward Allen.)*

Bricks and Brick Pavers

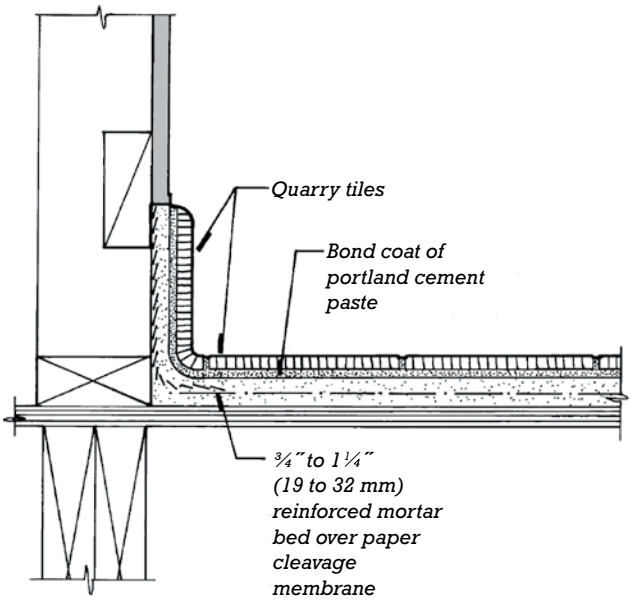
Both bricks and half-thickness bricks called *pavers* are used for finish flooring, with pavers often preferred because they add less thickness and dead weight to the floor (Figures 24.23 and 24.24). Bricks may be laid with their largest surface horizontal or on edge. As with stone and tile flooring, decorative joint patterns can be designed especially for each installation.

Quarry Tiles

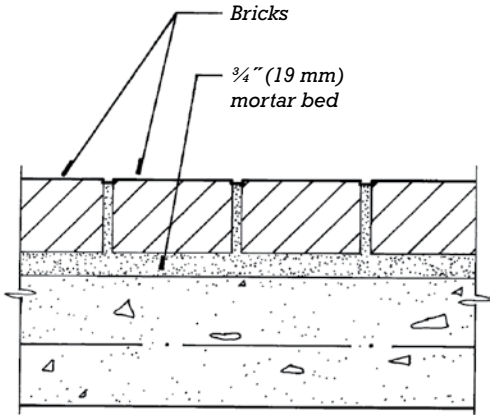
Quarry tiles are not, as might be guessed from their name, made of stone. They are simply large, fired clay tiles, usually square but sometimes rectangular, hexagonal, octagonal, or other shapes (Figures 24.23 and 24.25). Sizes range from about 4 inches (100 mm) to 12 inches (300 mm) square, with thicknesses ranging from ⅜ inch (9 mm) to a full inch (25 mm) for some handmade tiles. Quarry tiles are available in myriad earth colors, as well as in certain kiln-applied colorations. They may be set in a reinforced mortar bed, or, for lighter-duty applications work, they may be thin-set directly to a subfloor of wood panels or tile backer boards (Figure 24.27). (Tile-setting methods are discussed in more detail in Chapter 23.) It is important that any subfloor to which tiles are glued be sufficiently stiff; otherwise, flexing of the subfloor under changing loads will pop the tiles loose. Additional subfloor thickness and/or a stiff underlayment are advisable.

Ceramic Tiles

Fired clay tiles that are smaller than quarry tiles are referred to collectively as *ceramic tiles*. Ceramic tiles are usually glazed. The most common shape is square, but rectangles, hexagons, circles, and more



QUARRY TILE OVER WOOD SUBFLOOR



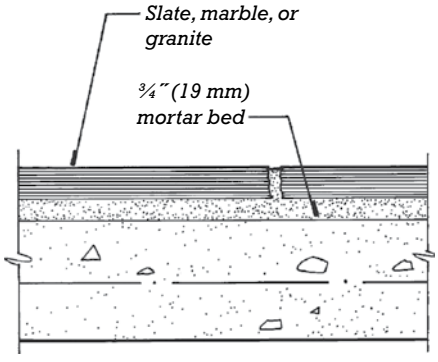
BRICK OVER CONCRETE SLAB

FIGURE 24.23
Examples of quarry tile, brick, and stone flooring (*opposite page*) details.

elaborate shapes are also available (Figures 24.26 and 24.28). Sizes range from ½ inch (13 mm) to 4 inches (100 mm) and more. Smaller-sized tiles are shipped from the factory with their faces adhered to larger backing sheets of plastic mesh or perforated paper. The tilesetter lays whole sheets of 100 or more tiles together in a single step rather than as individual units. The backing sheet is easily removed by wetting it after the tile adhesive has cured.

Grout color has a strong influence on the appearance of tile surfaces, just as the mortar used to lay brick and stone does. Many different premixed colors are available, or the tilesetter may custom-color a grout with pigments.

Methods of installing ceramic tile on interior wall surfaces, discussed in Chapter 23, apply to floor tiling as well (Figure 23.35). As in wall tiling applications, waterproofing membranes are integrated into floor tile assemblies in wet-use locations. Where tile is thickset over substrates that are cracked or prone to excessive deflection, a *slip sheet* (or *cleavage membrane*), usually consisting of ordinary building felt, may be inserted between the mortar base and the substrate to isolate the tile assembly and reduce the chance of tile cracking. Where tile is thin-set over difficult substrates, *crack isolation membranes* or *uncoupling membranes* that preserve the necessary bond between the thin-set compound and the substrate, but limit the transfer of stresses into the tile assembly, may be used.



STONE OVER CONCRETE SLAB

FIGURE 24.24
A floor of glazed brick pavers meets a planting bed constructed of brick masonry. *(Courtesy of Stark Ceramics, Inc.)*

Figure 24.25
Unglazed quarry tiles used as flooring and as a facing for columns and railings. *(Architect: Skidmore, Owings & Merrill. Interior designer: Duffy, Inc. Courtesy of American Olean Tile.)*

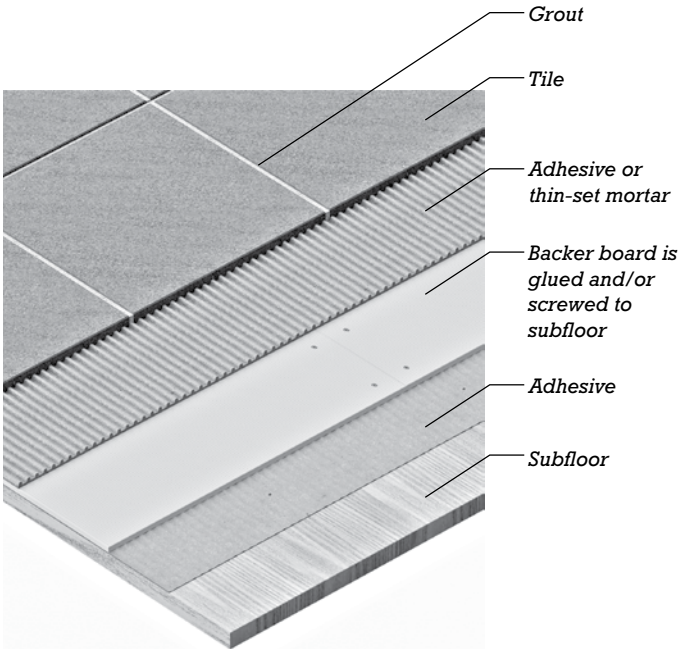


Figure 24.27
Quarry or ceramic tiles may be adhered to a cementitious backer board that is applied as an underlayment to a wood panel subfloor.

Figure 24.26
Square and octangular ceramic tiles in contrasting colors and laid in rich geometric patterns mark the transition between adjacent spaces in an early 20th century train hall. *(Photo by Joseph Iano.)*

Figure 24.28
Ceramic tile wainscoting and flooring in a bar. *(Architect: Daughn/Salisbury, Inc. Designer: Morris Nathanson Design. Courtesy of American Olean Tile.)*

Terrazzo

Terrazzo is an exceptionally durable flooring. It is made by grinding and polishing a concrete that consists of marble or granite chips selected for size and color in a matrix of colored portland cement or another binding agent. The polishing brings out the pattern and color of the stone chips. A sealer is usually applied to further enhance the appearance of the floor (Figure 24.29). Terrazzo may be formed in place or installed as factory-made tiles. For stair treads, window-sills, and other large components, terrazzo is often precast. Because of its endless variety of colors and textures, terrazzo is often used in decorative flooring patterns. The colors are separated from one another by *divider strips* of metal, plastic, or marble. The divider strips are installed in the underbed prior to placing the terrazzo, and are ground and polished flush in the same operation as the terrazzo itself.

FIGURE 24.29
A terrazzo floor in a residential entry uses divider strips and contrasting colors to create a custom floor pattern. *(Courtesy of National Terrazzo and Mosaic Association, Inc.)*

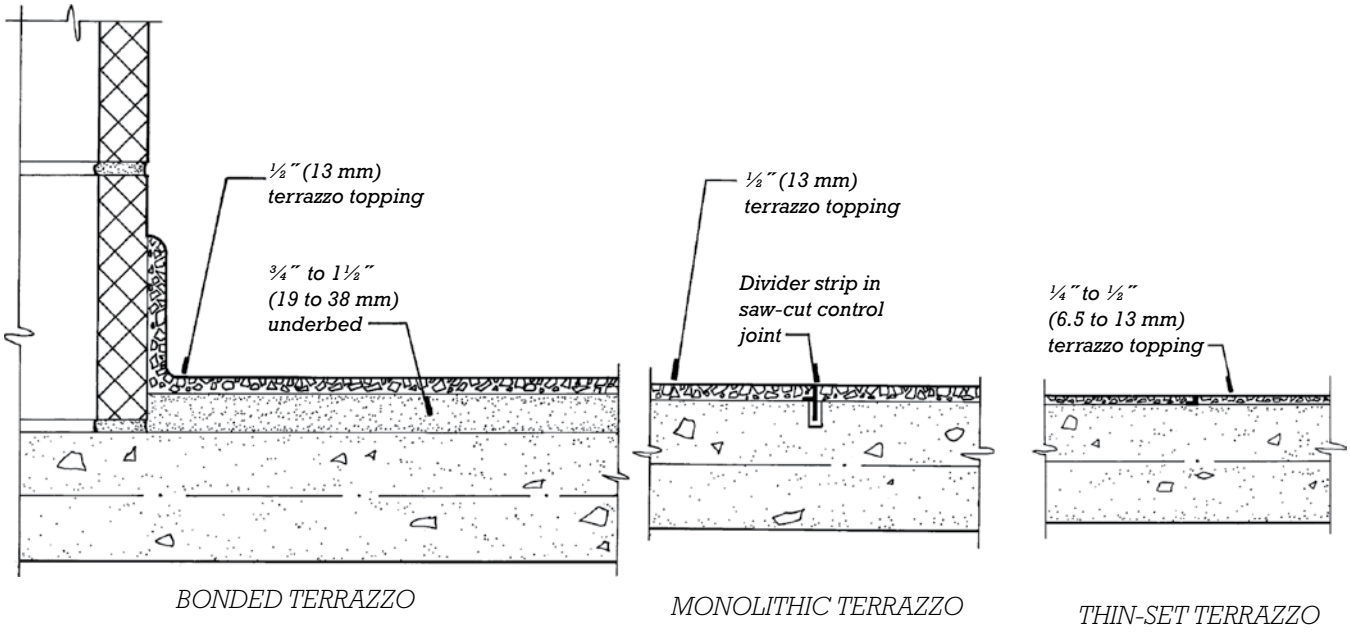


FIGURE 24.30
Sample bonded terrazzo, monolithic terrazzo, and thin-set terrazzo details.

Traditionally, terrazzo was installed over a thin bed of sand that isolated it from the structural floor slab, thus protecting it to some extent from movements in the building frame. However, this *sand cushion terrazzo* is thick—usually 2½ inches (64 mm)—and heavy. For greater economy and a thinner application, the sand bed is eliminated to produce *bonded terrazzo*, or both the sand bed and underbed may be eliminated with *monolithic terrazzo*. *Thin-set terrazzo*, made from epoxy resins, polyester resins, or polymer-modified cements, is the thinnest of all terrazzo installation methods (Figure 24.30). In any of these systems, a terrazzo baseboard can be formed and finished as an integral part of the floor, thus eliminating a dirt-catching seam where the floor meets the wall.

Wood and Bamboo

Wood Flooring

Wood is used in several different forms as a finish flooring material, the most common of which is solid wood tongue-and-groove *strip flooring*, typically ¾ inch (19 mm) thick and 1½ to 2¼ inches (38 to 57 mm) wide. Strip flooring can be made from many hardwood and softwood species, some of the more common being white oak, red oak, pecan, and maple (Figures 24.31, 24.32, and 24.33). The wood strips are held tightly together and *blind nailed* by driving nails diagonally through the upper interior corners of the tongues, where they are concealed from view once the next strip is installed. The entire floor is then sanded smooth, stained if desired, and finished with a varnish or other clear coating. When its surface becomes worn, the flooring can be restored to a new appearance by sanding and refinishing.

Solid wood flooring is also available in widths ranging from 3 to 8 inches (75 to 200 mm) called *plank flooring*. Because the wider planks are more prone to distortion with changes in moisture content, they are usually fastened through the face with countersunk and plugged screws in addition to, or instead of, being blind nailed along their edges.

For greater economy, factory-made wood flooring consisting of finish wood veneers laminated to a plywood-like core, called *engineered wood flooring*, is used. Typically ⅜ or ½ inch (10 or 13 mm) thick, it is glued to the subfloor with a

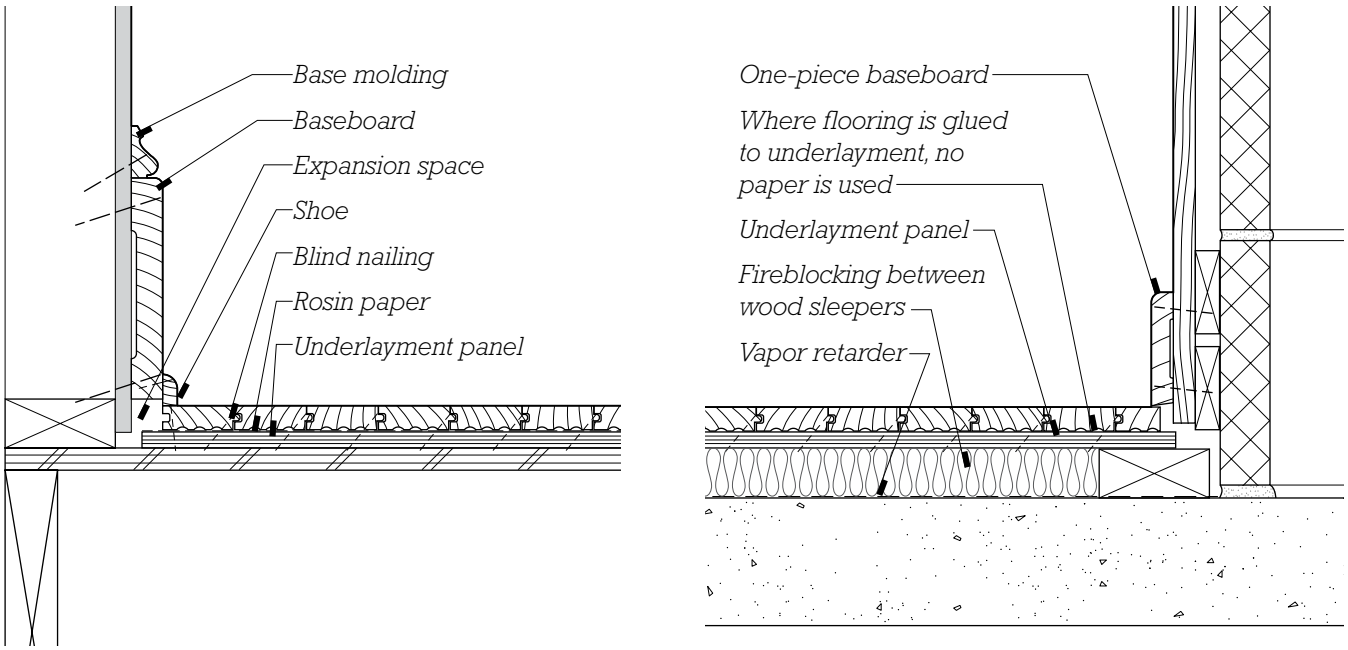


FIGURE 24.31

At left, hardwood strip flooring over a wood floor structure. A traditional three-piece base is shown. The base molding and shoe are thinner, more flexible trim pieces that readily conform to irregularities in the wall or floor. A gap is left at the perimeter of the floor to allow for expansion and contraction of the flooring. A rosin paper slip sheet may be installed under the flooring to ease installation and help prevent squeaks in the finished floor. The underlayment panel provides a clean, uniform substrate and adds stiffness to the assembly. It can be particular helpful when the flooring strips run parallel to the floor joists. At right, the same flooring installed over sleepers and a concrete slab. When flooring is glued to the underlayment or subfloor, no slip sheet is used. In noncombustible buildings, concealed space under wood flooring must be fireblocked to prevent the undetected spread of fire. Here, this is accomplished with mineral wool filling the spaces between sleepers. A vapor retarder is placed over the concrete slab to reduce the rate of moisture escaping from the concrete and protect the wood flooring from excessive moisture levels.

Interactive Exercise

mastic adhesive rather than nailed. The laminated construction of engineered wood flooring makes it less sensitive to changes in moisture content and more dimensionally stable than solid wood flooring. For this reason, it is considered better suited for use on basement slabs on grade or in other locations exposed to high humidity levels. Because the finish surface is a thin veneer, most engineered wood floorings are not able to withstand subsequent sanding and refinishing.

Parquet is wood flooring of varying hues arranged in patterns. It may be made of solid wood strips assembled in the field, of factory-preassembled blocks made from solid wood strips, or of engineered wood.

Some wood flooring systems are not nailed or glued to the subfloor, but instead "float" above it on a thin pad of resilient foam. These so-called *floating floors* are made by connecting the individual pieces of flooring together at the edges to make one continuous piece as large as the room in which the flooring is laid. Edge gluing is the most common way of making this connection, but systems also rely on metal clips or interlocking edge details. A gap is left at the edges to permit expansion and contraction of the floor. This is later covered with baseboard trim. Most floating floors are made of engineered wood flooring, which is more dimensionally stable than solid wood flooring.

Many types of wood flooring are available with factory-applied finishes. When the installation of conventional unfinished flooring begins on a project, it may require the complete cessation of other construction activities for a number of days while the flooring is installed and sanded, and several coats of finish are applied and allowed to dry. With factory- finished flooring, the time required for a complete installation and the impact on the other activities are minimized. Prefinished flooring, however, cannot be sanded after installation, so these products are supplied with eased edges (a slight beveling of the corners along the finish face edges) that hide minor differences in level between adjacent pieces of flooring after installation.

FIGURE 24.32
An installer of hardwood strip flooring uses a pneumatic nail gun to drive the diagonal blind nails that fasten the flooring to the subfloor. The nail gun is a special type that is activated by a blow from a mallet that also serves to drive the flooring pieces tightly together. Asphalt-saturated felt paper cushions the flooring and helps to prevent squeaking. *(Photo by Rob Thallon.)*

FIGURE 24.33
Oak strip flooring in a hair salon. Notice the use of exposed ducts and a lighting track at the ceiling. *(Architects: Michael Rubin and Henry Smith-Miller in association with Kenneth Cohen. Courtesy of the Oak Flooring Institute.)*

Factory finishing is especially common with engineered wood flooring. Because the finish veneer is thin and can never be sanded and refinished, an especially hard, wear-resistant acrylic resin finish is applied in the factory that helps to prolong the life of the floor.

Plastic laminate flooring is composed of planks or large tiles that have a wood composite core and a wearing layer of high-density plastic laminate much like that used on countertops. It is almost always laid as a floating floor. The laminate is usually patterned to resemble wood, but other patterns are also available. Most laminate floorings may be used in kitchens or baths if a sealant is applied around the perimeter of the floor to keep water from getting beneath it.

Exceptionally long-wearing industrial *wood block flooring* is made of small blocks of wood set in adhesive with their grain oriented vertically. Although this type of floor is relatively high in first cost, it is economical for heavily used floors and is sometimes chosen for use in public spaces because of the beauty of its pattern and grain.

Bamboo Flooring

Bamboo, a rapidly growing grass, can be used to produce flooring products very much like those of wood. The manufacturing process entails slicing the hollow bamboo shoots into strips, processing the strips to remove starch, laminating and gluing the strips under pressure, and then machining the laminated stock into the final flooring profile. Laminations may be oriented either vertically or horizontally within the strip, creating a surface appearance analogous to either flat grain or edge grain in solid woods.

Bamboo flooring is harder and more dimensionally stable than conventional wood flooring. Its natural color is light, akin to that of maple. A darker amber hue can be achieved by pressure steaming, a process called carbonization. Like wood, bamboo flooring can be provided either as solid strip, made entirely of bamboo laminations, or as an engineered product consisting of a roughly ⅛ -inch (3-mm)-thick bamboo finish layer adhered to a laminated base of conventional wood. It may be provided unfinished or factory finished.

Resilient Flooring

The oldest *resilient flooring* material is *linoleum*, a sheet material made of ground cork in a linseed oil binder over a burlap backing. *Asphalt tiles* were later developed as an alternative to linoleum, but the majority of today's resilient sheet floorings and tiles are made of compounds of vinyl or rubber. The primary advantages of resilient floorings are the wide range of available colors and patterns, moderately high durability, and low initial cost.

Vinyl composition tile (*VCT*), made of one or more vinyl resins in combination with binders, pigments, and fillers (VCT may consist of as much as 85 percent limestone filler), has the lowest installed cost of any flooring material except concrete and is used in vast quantities on the floors of residences, offices, classrooms, and retail spaces. Other common resilient tile flooring materials include *solid vinyl tile* (*SVT*), with higher vinyl content and greater durability than VCT; and *rubber floor tile*, made from vulcanized natural or synthetic

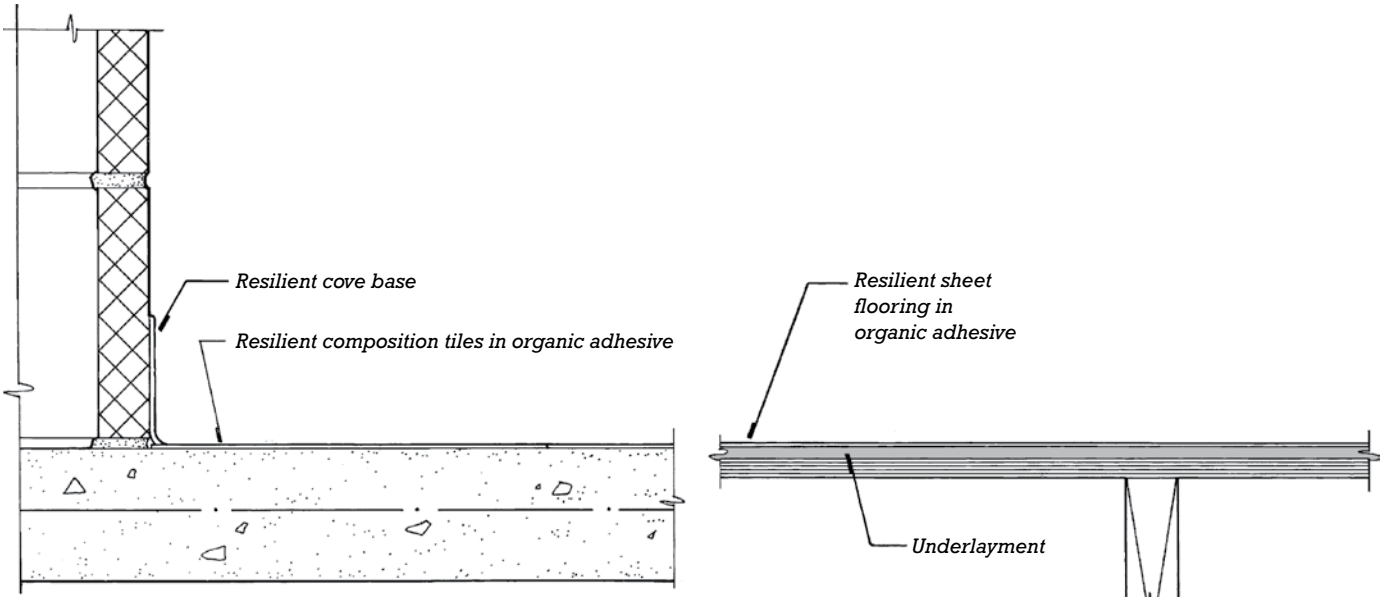


FIGURE 24.34
Typical installation details for resilient flooring. At the left, resilient tiles applied directly to a steel-trowel-finish concrete slab, with a cove base adhered to a concrete masonry partition. At the right, resilient sheet flooring on underlayment and a wood joist floor structure.

rubber compounds and various additives. Floor tile thickness is typically $^1/_8$ inch (3 mm) or slightly less. The most common tile size is 12 inches (305 mm) square, although other sizes, up to 36 inches (914 mm) square, are also available.

The most common *resilient sheet flooring* materials are solid vinyl and rubber. Resilient floorings of linoleum, cork, and other materials are also available. Each offers particular characteristics of durability and appearance. Thicknesses of sheet flooring are also on the order of ⅛ inch (3 mm), slightly thinner for lighter-duty floorings, and slightly thicker if a cushioned back is added to the product. Sheet floorings are furnished in rolls 4.9 to 12 feet (1.5 to 3.6 m) wide. If they are skillfully installed, the seams between sheet strips are virtually invisible.

Most resilient flooring materials are glued to the concrete or wood surface of the structural floor (Figures 24.34, 24.35, and 24.36). The resilient materials themselves are so thin and deformable that they show even the slightest irregularities in the floor deck beneath. Concrete surfaces to which resilient materials will be applied must first be scraped clean of construction debris and spatters. Wood panel decks are covered with a layer of smooth *underlayment panels*, usually of hardboard, particleboard, or sanded plywood, to provide a smoother substrate for the resilient flooring materials. Joints between underlayment panels are offset from joints in the subfloor to eliminate soft spots. The thickness of the underlayment is chosen to make the surface of the resilient flooring level with the surfaces of flooring materials such as hardwood and ceramic tile that are used in surrounding areas of the building. Leveling compounds, gypsum, or cement-based plaster-like materials that can be feathered to a very thin edge are also used to fill in minor low spots in the floor surface before the resilient materials are installed.

Various flooring accessories, such as bases, stair treads, and stair nosings, are also made of vinyl and rubber compounds. *Cove base* is the base most commonly used with resilient flooring (Figures 24.34 and 24.35). *Straight base*, also called *flat* or *toeless base*, has no cove or toe and is most commonly used with carpet flooring. *Fit-to-floor base*, or *butt-to base*, has a square-edged toe the same thickness as the floor covering; it butts tightly to the finish flooring, creating a flush transition between the two.

Figure 24.35
Vinyl composition tile and a vinyl cove base. Notice how the base is simply folded around the outside corner of the partition. *(Courtesy of Armstrong World Industries.)*

Figure 24.36
Sheet vinyl flooring can be flash coved to create an integral base that is easily cleaned for use in healthcare facilities, kitchens, and bathrooms. The seams are welded to eliminate dirt-catching cracks. *(Courtesy of Armstrong World Industries.)*

Carpet

Carpet is manufactured in fibers, styles, and patterns to meet almost any flooring requirement, indoors or out, except for rooms that require thorough sanitation, such as hospital rooms, food-processing facilities, and toilet rooms. Some carpets are tough enough to wear for years in public corridors (Figure 24.37); others are soft enough for intimate residential interiors. The costs of carpeting are often competitive with those of other flooring materials of similar quality, whether they are measured on an installed-cost or life-cycle-cost basis. Slightly more than one-half of all carpet sold in North America is made with nylon fibers; more than an additional one-third is made with polypropylene; the remainder is made with other synthetics and natural fibers.

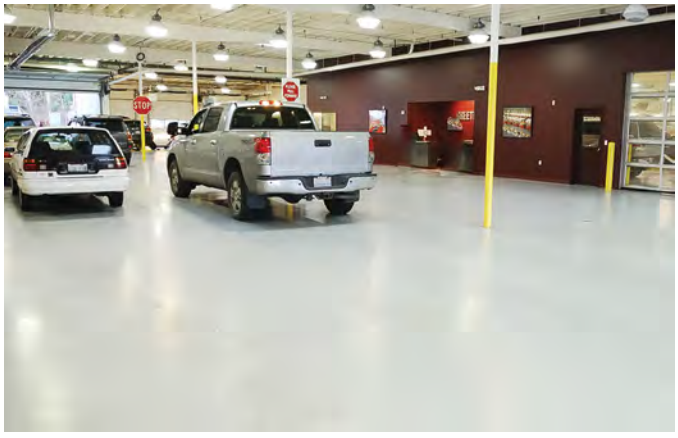
There are four ways to install carpet: The two most common are gluing directly to the floor deck (*direct glue-down installation*) and stretching over a *carpet pad*, or *cushion*, and attaching the perimeter by means of a *tackless strip* (*stretch-in installation*). The tackless strip (also called a *tackstrip*) is a continuous length of wood, fastened to the floor, that has protruding spikes along the top to catch the backing of the carpet and hold it taut as it is stretched into place by the installers. Less frequently, carpet pad is glued to the floor deck and the carpet is then glued to the pad (*double glue-down installation*), or carpet with a factory-attached pad is glued to the floor deck (*attached cushion installation*).

If carpet or carpet tile is laid directly over a wood panel subfloor such as plywood, the panel joints perpendicular to the floor joists should be blocked beneath to prevent movement between sheets. Tongue-and-groove plywood subflooring accomplishes the same result without blocking. Or, a layer of underlayment panels may be added over the subfloor with its joints offset from those in the subfloor.

Historically, both carpet and resilient flooring materials have been significant sources of indoor VOC emissions and adverse indoor air quality impacts. More recently, manufacturers have reformulated and developed new materials to lower emissions from their installed products. They have also established third-party standards-setting programs to certify low-emitting and environmentally sustainable standards for their products. See this chapter's sidebar, "Sustainability and Finish Ceilings and Floors," for more information.

FIGURE 24.37
Wall-to-wall carpeting in a commercial installation. *(Courtesy of Armstrong World Industries.)*

FIGURE 24.38
A seamless, epoxy traffic coating provides a durable, easy-to-clean, and chemical-resistant finish flooring for this automobile repair garage.



Carpet Tile

Carpet materials are also manufactured in tile form, with typical sizes ranging from 18 to 36 inches (457 to 914 mm) square. In comparison to sheet carpet, tiles are easier to deliver, store, handle, and install; they allow easier spot replacement; they permit ready underfloor access; and they are compatible with raised-access flooring systems. Carpet tile installation methods include *glue-down*, in which every tile is adhered to the subfloor; *partial glue-down*, in which only periodically spaced tiles are adhered to the subfloor; and *free-lay*, in which interlocking tiles are laid without any adhesive.

Fluid-Applied Flooring

Fluid-applied flooring is applied as a thin liquid coating over concrete or wood decking and then cures to a seamless, easy-to-clean finish floor surface. Depending on formulation, coverings satisfying a wide range of requirements for durability, chemical resistance, ease of installation, and appearance are possible. Though more expensive to install than other resilient flooring options, their greater durability makes these systems often less expensive when costs are considered over the full life of the flooring.

Urethane and *epoxy floor coatings* are the most common. A typical application over concrete consists of preparation of the concrete surface by grinding or blasting, application of primer to ensure good adhesion between the substrate and the following layers, one or two coats of the primary flooring material, possibly with the addition of sand, quartz aggregate, rubber chips, or other fillers, and a top coat and/or sealer. Thickness of the finished flooring typically ranges from 3/16 to 3/8 inch (5 to 10 mm), although both thinner and thicker applications are also possible.

Acrylic (methyl methacrylate monomer, or *MMA*) *floor coatings*, though high in VOC emissions, cure in as little as one hour. They are popular where rapid turn-around time in the floor coating process is especially important. Thin, *UV-curable coatings* emit no VOCs and cure virtually instantaneously as a machine with a controlled-intensity ultraviolet lamp is rolled across the wet material.

Cementitious overlays are formulations of polymers, portland cement, fine sand, and other ingredients that are applied as self-leveling fluids. Once cured, they form durable, polishable, integrally colored, finished floor surfaces.

Traffic coatings are fluid-applied products, most commonly urethanes, formulated for exterior exposure, and able to tolerate both foot and vehicular traffic. They find frequent use as coatings for parking garage decks, exterior balconies, and elsewhere where a low-cost and waterproof coating is required (Figure 24.38).

MasterFormat Sections for Finish Ceilings and Floors

03 54 00	**CAST UNDERLAYMENT**
07 18 00	**TRAFFIC COATINGS**
04 42 00	**WOOD PANELING**
09 22 00	**SUPPORTS FOR PLASTER AND GYPSUM BOARD**
09 30 00	**TILING**
09 30 13	Ceramic Tiling
09 30 16	Quarry Tiling
09 30 33	Stone Tiling
09 31 00	**THIN-SET TILING**
09 32 00	**MORTAR BED TILING**
09 51 00	**ACOUSTICAL CEILINGS**
09 51 23	Acoustical Tile Ceilings
09 51 53	Direct-Applied Acoustical Ceilings
09 54 00	**SPECIALTY CEILINGS**
09 58 00	**INTEGRATED CEILINGS**
09 60 00	**FLOORING**
09 60 13	Acoustic Underlayment
09 62 00	**SPECIALTY FLOORING**
09 62 23	Bamboo Flooring
09 62 29	Cork Flooring
09 63 00	**MASONRY FLOORING**
09 64 00	**WOOD FLOORING**
09 65 00	**RESILIENT FLOORING**
09 66 00	**TERRAZZO FLOORING**
09 67 00	**FLUID-APPLIED FLOORING**
09 69 00	**ACCESS FLOORING**

Key Terms

Ceiling Attenuation Class (CAC)
Articulation Class (AC)
plenum
membrane ceiling, membrane fire protection
suspended ceiling
hanger wire
perforated gypsum panel
acoustical ceiling
lay-in panel
exposed grid
concealed grid
integrated ceiling system
metal panel ceiling
linear metal ceiling
suspended wood ceiling
fabric-wrapped ceiling panel
stretched-fabric ceiling system
interstitial ceiling
closed-loop recycling
acoustic underlayment
coefficient of friction (COF)
static coefficient of friction (SCOF)
dynamic coefficient of friction (DCOF)
static control flooring
cellular raceway
cellular steel decking
poke-through fitting
raised access flooring
undercarpet wiring system
self-leveling underlayment
concrete hardener
paver
quarry tile
ceramic tile
slip sheet, cleavage membrane
crack isolation membrane
uncoupling membrane
terrazzo
divider strip
sand cushion terrazzo
bonded terrazzo
monolithic terrazzo
thin-set terrazzo
strip flooring
blind nail
plank flooring
engineered wood flooring
parquet
floating floor
plastic laminate flooring
wood block flooring
resilient flooring
linoleum
asphalt tile
vinyl composition tile (VCT)
solid vinyl tile (SVT)
rubber floor tile
resilient sheet flooring
underlayment panel
cove base
straight base, flat base, toeless base
fit-to-floor base, butt-to base
carpet
direct glue-down installation
carpet pad, cushion
tackless strip, tackstrip
stretch-in installation
double glue-down installation
attached cushion installation
glue-down tile installation
partial glue-down tile installation
free-lay tile installation
fluid-applied flooring
urethane floor coating
epoxy floor coating
acrylic (MMA) floor coating UV-curable floor coating
cementitious overlay
traffic coating

Review Questions

1. List the potential range of functions of a finish ceiling and of a finish floor.

2. What are the advantages and disadvantages of a suspended ceiling compared to those of a tightly attached ceiling?

3. When designing a building with its structure and mechanical equipment left exposed at the ceiling, what precautions should you take to ensure a satisfactory appearance?

4. What does underlayment do? How should it be laid? What does acoustical underlayment do?

5. List several different approaches to the problem of running electrical and communications wiring beneath a floor of a building framed with steel or concrete.

Exercises

1. Visit some rooms that you happen to like in nearby buildings—classrooms, auditoriums, theaters, restaurants, bars, museums, shopping centers—both new buildings and old. For each, identify the ceiling and floor finishes used. Why was each material chosen? Sketch details of critical junctions between materials. What does each room sound like—noisy, hushed, "live"? How does this acoustical quality relate to the floor and ceiling materials? What is the quality of the illumination in the room, and what role do ceiling and floor materials play in creating this quality?

2. Consult current architectural magazines for interior photographs of buildings that appeal to you. What ceiling and floor materials are used in each? Why?

Selected References

Because so many ceiling and flooring materials and systems are proprietary, much of the best information on ceiling and floor finishes is to be found in manufacturers' literature. Certain generic products are, however, well documented in trade association literature:

Carpet and Rug Institute. *CRI 104 Carpet Installation Standard for Commercial Carpet.* Dalton, GA, updated regularly.

Industry-standard recommendations for the installation of carpet of all types, available from this association's website as a free download.

Ceilings and Interior Systems Construction Association. *Ceiling Systems Handbook. St. Charles*, IL, updated frequently.

Aimed at construction workers, this manual covers everything pertaining to the installation of ceilings.

Natural Stone Institute. *Dimension Stone Design Manual.* Oberlin, OH, updated regularly.

This binder provides comprehensive guidance on the design, specification, and installation of all types of stone flooring.

National Wood Flooring Association. *Installation Guidelines.* Chesterfield, MO, updated regularly.

This manual provides industry-standard recommendations for the installation of all kinds of wood flooring.

Tile Council of North America. *TCNA Handbook for Ceramic Tile, Glass, and Stone Tile Installation.* Anderson, SC, updated regularly.

This is the definitive standard for ceramic tile installation materials and methods. More than 100 methods of installation for floors and walls, both interior and exterior, are illustrated and specified. Guidelines for selecting appropriate installation methods based on project requirements are also included.

Websites

Armstrong Flooring, Armstrong World Industries (ceilings): www.armstrong.com

Carpet America Recovery Effort (CARE): carpetrecovery.org

Carpet and Rug Institute (CRI): www.carpet-rug.org

Ceilings and Interior Systems Construction Association: www.cisca.org

Forbo Flooring Systems: https://www.forbo.com/flooring/en-us

HH Robertson: www.hhrobertson.com

Mannington Floors: www.mannington.com

Maple Flooring Manufacturers Association (MFMA): www.maplefloor.org

National Terrazzo & Mosaic Association (NTMA): www.ntma.com

National Wood Flooring Association (NWFA): www.nwfa.org

Natural Stone Institute: www.naturalstoneinstitute.org

Resilient Floor Covering Institute (RFI): www.rfci.com

Tile Council of North America (TCNA): www.tcnatile.com

APPENDIX

Densities and Coefficients of Thermal Expansion of Common Building Materials

	Density		Coefficient of Thermal Expansion		
Material	**lb/ft³**	**kg/m³**	**in./in.-°F × 10⁶**	**mm/mm-°C × 10⁶**	
Wood (seasoned)					
Douglas fir	32	510	2.1	3.8	parallel to grain
			32	58	perpendicular to grain
Pine	26	415	3.0	5.4	parallel to grain
			19	34	perpendicular to grain
Oak, red or white	41–46	655–735	2.7	4.9	parallel to grain
			30	54	perpendicular to grain
Masonry					
Limestone	130–170	2080–2720	4.4	7.9	
Granite	165–170	2640–2720	4.7	8.5	
Marble	165–170	2640–2720	7.3	13.1	
Brick	100–140	1600–2240	3.6	6.5	
Concrete masonry units	75–145	1200–2320	5.2	9.4	
Concrete					
Normal-weight concrete	145	2320	5.5	9.9	
Metals					
Steel	490	7850	6.5	11.7	
Stainless steel, Type 304	490	7850	9.9	17.8	
Aluminum	165	2640	12.8	23.1	
Copper	556	8900	9.3	16.8	
Finish Materials					
Gypsum board	43–50	690–800	9.0	16.2	
Gypsum plaster, sand	105	1680	7.0	12.6	
Glass	156	2500	5.0	9.0	
Acrylic glazing sheet	72	1150	41.0	74.2	
Polycarbonate glazing sheet	75	1200	44.0	79.6	
Polyethylene	57–61	910–970	85.0	153	
Polyvinyl chloride (PVC)	75–106	1200–1700	40.0	72.0	

Unit Conversions

Inch-Pound (U.S. Customary)	Metric (SI)	Metric (SI)	Inch-Pound (U.S. Customary)
1 in.	25.40 mm	1 mm	0.3937 in.
1 ft	304.8 mm	1 m	39.37 in.
1 ft	0.3048 m	1 m	3.2808 ft
1 lb	0.4536 kg	1 kg	2.205 Ib
1 lb	4.448 N	1 N	0.2248 lb
1 lb	0.0004536 metric ton (tonne)	1 metric ton (tonne)	2205 lb
1 ton (short ton)	0.9072 metric ton (tonne)	1 metric ton (tonne)	1.102 ton (short ton)
1 ft^2	0.0920 m^2	1 m^2	10.76 ft^2
1 ft^3	0.02832 m^3	1 m^3	35.31 ft^3
1 ft^3	28.32 L	1 L	0.03531 ft^3
1 gal	3.785 L	1 L	0.2642 gal
1 psi	6.894 kPa	1 kPa	0.1451 psi
1 psi	0.006894 MPa	1 MPa	145.1 psi
1 lb/ft^2	4.882 kg/m^2	1 kg/m^2	0.2048 lb/ft^2
1 lb/ft^2	0.04788 kPa	1 kPa	20.89 lb/ft^2
1 lb/ft^3	16.02 kg/m^3	1 kg/m^3	0.06243 lb/ft^3
1 lb/ft^3	0.01602 g/cm^3	1 g/cm^3	62.43 lb/ft^3
1 ft/min	0.005080 m/s	1 m/s	196.9 ft/min
1 cfm	0.0004719 m^3/s	1 m^3/s	2119 cfm
1 cfm	0.4739 L/s	1 L/s	2.119 cfm
1 BTU	0.2522 kcal	1 kcal	3.966 BTU
1 BTU	1.055 kJ	1 kJ	0.9478 BTU
1 BTU	0.001055 MJ	1 MJ	947.8 BTU
1 BTUH	0.2931 W	1 W	3.412 BTUH
Thermal Resistance and Conductance			
R 1 (ft^2-hr-°F/BTU)	RSI 0.1761 (m^2-°K/W)[a]	RSI 1 (m^2-°K/W)[a]	R 5.678 (ft^2-hr-°F/BTU)
U 1 (BTU/ft^2-hr-°F)	U 5.678 (W/m^2-°K)[a]	U 1 (W/m^2-°K)[a]	U 0.1761 (BTU/ft^2-hr-°F)
Vapor Permeance			
1 perm (grains/hr-ft^2-in. Hg)	57.21 ng/s-m^2-Pa	1 ng/s-m^2-Pa	0.01748 perms (grains/hr-ft^2-in. Hg)
Air Permeance			
1 cfm/sf@1.57 psf	5.080 L/s-m^2@75 Pa	1 L/s-m^2@75 Pa	0.1968 cfm/sf@1.57 psf
Embodied Energy			
1 BTU/sf	0.01136 MJ/m^2	1 MJ/m^2	88.06 BTU/sf
1 BTU/lb	2.326 MJ/tonne	1 MJ/tonne	0.4299 BTU/lb
Other Conversions			
1 mil = 0.001 in.		1 Pa = 0.1020 kg/m^2	
1 in. = 1000 mil		1 kg/m^2 = 9.807 Pa	

[a] Metric thermal conductance and resistance units may be expressed with either "°K" or "°C." In either case, the conversion factors are the same, because a 1-degree difference in either the Celsius or Kelvin temperature scale is the same.

GLOSSARY

A

AAC *See* **autoclaved aerated concrete**.

AAMA American Architectural Manufacturers Association, a trade organization that develops standards for windows, doors, skylights, storefront, and curtain wall systems.

AC *See* **Articulation Class**.

Accelerating admixture An *admixture* that causes concrete or mortar to cure more rapidly.

Access flooring A raised finish floor surface consisting of small, individually removable panels beneath which wiring, ductwork, and other building services may be installed.

Access standard Regulations or technical standards ensuring that buildings are usable by persons with physical, cognitive, and sensory disabilities.

Acoustic insulation Fibrous or board material used to reduce sound transmission through a wall or ceiling assembly.

Acoustical ceiling A ceiling of fibrous tiles that are highly absorbent of sound energy.

ACQ *See* **alkaline copper quat**.

Acrylic A transparent plastic material widely used in sheet form for glazing windows and skylights; a modifier added to plasters, paints, and cements to enhance various performance properties of the material.

Actual dimension The true dimension of a material, as distinct from its *nominal dimension*.

ADA *See* **airtight drywall approach**.

ADA *See* **Americans with Disabilities Act**.

Admixture In a concrete or mortar, a chemical ingredient added for the purpose of altering one or more properties of the mixed material, either in its plastic working state or after it has hardened.

Advanced framing techniques A wood light framing system that minimizes redundant framing members, reducing the amount of lumber required and increasing the thermal efficiency of the insulated frame.

Aerogel A silicon-based foam with relatively high thermal resistance used in insulating blankets and insulated glazing units.

AESS *See* **architecturally exposed structural steel**.

Aggregate Inert particles, such as sand, gravel, crushed stone, or expanded minerals, in a concrete, mortar, plaster, or earthwork.

Air barrier A material that resists air leakage through a building assembly.

Air barrier assembly An interconnected assemblage of air barrier materials that resist air leakage through wall, roof, and floor assemblies.

Air barrier system An interconnected collection of air barrier assemblies responsible for the overall air leakage performance of a building.

Airborne sound Sound transmitted through pressure waves in the air, frequently referring to the transmission of sound through partitions or walls and associated with *Sound Transmission Class* ratings. *See also* **structure-borne sound**.

Air-entraining admixture An *admixture* that causes a controlled quantity of stable microscopic air bubbles to form in concrete or mortar during mixing, usually for the purposes of increasing workability and resistance to freeze-thaw conditions.

Air permeance A measure of a material's permeability to airflow. A low air permeance is a desirable characteristic of an *air barrier* material.

Air-supported structure A structure, usually long span, with a fabric roof supported by a higher air pressure inside the structure relative to outside the structure.

Airtight drywall approach (ADA) An *air barrier system* relying on gypsum board interior finish and the sealing of joints between framing members of a light frame building, serving to restrict the flow of air through the exterior walls and roof.

Air and water-resistive barrier (AWB) A membrane or material used to resist the passage of liquid water and air through the *building enclosure*.

Air-weather barrier *See* **air and water-resistive barrier**.

AISC American Institute of Steel Construction. A trade association that establishes standards for the use of structural steel in buildings and other structures.

Albedo *See* **solar reflectance**.

Alloy A metal composed of two or more metals or of a metal and other nonmetallic constituents.

Aluminum A silver-colored *nonferrous metal* that naturally forms a self-protecting oxide layer.

Americans with Disabilities Act (ADA) A federal regulation establishing equal access for persons with disabilities to public accommodations, commercial facilities, and transportation facilities.

Anchor Any of a variety of mechanical devices used to fasten or connect one material or member to another.

Anchor bolt A bolt embedded in concrete for the purpose of fastening a building frame to a concrete or masonry foundation.

Angle A structural section of steel, aluminum, or other material whose profile resembles the letter *L*.

Angle of repose *See* **maximum allowable slope**.

Annealed Cooled under controlled conditions to minimize internal stresses, usually referring to iron, steel, aluminum, or glass members.

Anode The metal in a *galvanic couple* that experiences accelerated corrosion.

Anodizing An electrolytic process that forms a permanent protective oxide coating on aluminum, with or without added color.

ANSI American National Standards Institute, an organization that fosters the establishment of voluntary industrial standards.

Anticlastic Saddle-shaped or having curvature in two opposing directions.

APP *See* **atactic polypropylene**.

Apparent Sound Transmission Class (ASTC) *See* **Field Sound Transmission Class (FSTC)**.

Appearance grading The grading of wood for its appearance, as distinct from its structural properties; not to be confused with *visual grading*.

Apron The finish piece that covers the joint between a window stool and the wall finish below.

Arch A structural device that supports a vertical load by translating it into axial inclined forces at its supports.

Architectural concrete Concrete intended as a finish surface and produced to a higher-quality standard.

Architecturally exposed structural steel (AESS) Structural steel intended to be left exposed in the finished building and fabricated and installed to a higher-quality standard.

Architectural sheet metal roofing A roof covering made up of sheets of metal in a traditional shop- or site-fabricated pattern such as standing seam, flat seam, or batten seam.

Architectural Woodwork Institute (AWI) A trade organization that develops standards for custom millwork.

Arc welding A process of joining two pieces of metal by melting them together at their interface with a continuous electric spark and adding a controlled additional amount of molten metal from a metallic electrode.

Articulation Class (AC) A measure of a finish ceiling's absorption and reflection of sound, particularly with regard to speech clarity in an open office environment.

Ash dump A door in the *underfire* of a fireplace that permits ashes from the fire to be swept into a chamber beneath, from which they may be removed at a later time.

Ashlar Squared stonework.

Asphalt A tarry brown or black mixture of hydrocarbons; one type of *bitumen*.

Asphalt roll roofing A continuous sheet of the same roofing material used in *asphalt shingles*.

Asphalt-saturated felt A water-resistive sheet material usually consisting of matted cellulose fibers that have been impregnated with asphalt; used to provide a weather-protective layer in an exterior wall or roof assembly. Also called *building felt*.

Asphalt shingle A roofing unit composed of a heavy organic or inorganic felt saturated with asphalt and faced with mineral granules.

ASTC *See* **Apparent Sound Transmission Class**.

ASTM Formerly the American Society for Testing and Materials; an organization that promulgates standards for testing, materials, and methods of building construction.

Atactic polypropylene (APP) An amorphous form of polypropylene used as a modifier in *modified bitumen roof membrane*.

Auger A helical tool for creating cylindrical holes.

Autoclaved aerated concrete (AAC) Concrete formulated to contain a large percentage of gas bubbles as a result of a chemical reaction that takes place in an atmosphere of steam.

AWB *See* **air and water-resistive barrier**.

AWI *See* **Architectural Woodwork Institute**.

Awning window A window that pivots on a horizontal axis at the top edge of the sash and projects toward the outdoors.

Axial In a direction parallel to the long axis of a structural member.

B

Backer board A water-resistant board, used as a base for *thin-set tile* applications, usually composed of fiber-reinforced cement or glass-mat-faced gypsum.

Backer rod A flexible, compressible strip of plastic foam inserted into a joint to limit the depth to which *gunnable sealant* can penetrate.

Backfill Earthen material used to fill the excavation around a foundation; the act of filling around a foundation.

Backup bar A small rectangular strip of steel applied beneath a joint to provide a solid base for beginning a weld between two steel structural members.

Backup wall A vertical plane of masonry, concrete, or wood framing used to support a thin facing, such as a single *wythe* of brickwork.

Ballast A heavy material installed over a roof membrane to prevent wind uplift and shield the membrane from sunlight.

Balloon frame A wooden building frame composed of closely spaced members nominally 2 inches (38 mm) thick, in which the wall members are single pieces that run from the top of the foundation to the underside of the roof framing.

Baluster A vertical member that serves to fill the opening between a handrail and a stair or floor.

Band joist A wooden joist running perpendicular to the primary direction of the joists in a floor and closing off the floor platform at the outside face of the building. Also called a *rim joist*.

Bar A small rolled steel shape, usually round or rectangular in cross section; a *steel reinforcing bar* used for reinforcing concrete.

Barrel shell A scalloped roof structure of reinforced concrete that spans in one direction as a barrel vault and in the other as a folded plate.

Barrel vault A segment of a cylindrical surface that spans as an arch.

Barrier wall An exterior building wall whose watertightness depends on its freedom from passages through the wall. Also called a *face-sealed wall*.

Basalt A dense and durable igneous rock, usually dark gray; classified by ASTM C119 in the Granite group.

Baseboard A strip of finish material placed at the junction of a floor and a wall to create a neat intersection and to protect the wall against damage from feet, furniture, and floor-cleaning equipment.

Base-coat plaster One or more preparatory plaster coats that provide a flat, solid surface suitable for the application of the final finish coat plaster. *See also* **scratch coat** and **brown coat**.

Base flashing The flashing at the edges of a low-slope roof membrane that turns up against the adjacent face of a parapet, wall, or curb; frequently overlapped by a *counterflashing*.

Base isolator A device at foundation level that diminishes the transmission of seismic motions to a building.

Baseplate A steel plate inserted between a column and a foundation to spread the concentrated load of the column across a larger area of the foundation.

Basic oxygen process A steel-making process in which a stream of pure oxygen is introduced into a batch of molten iron so as to remove excess carbon and other impurities.

Batten A strip of wood or metal used to cover the gap between two adjoining boards or panels.

Batten seam A seam, roughly square in profile, in *architectural sheet metal roofing*.

Batter board Boards mounted on stakes outside the excavation area of a building used to preserve locations for string lines marking the corners of the building foundation.

Bay A rectangular area of a building defined by four adjacent columns; a portion of a building that projects from a façade.

Bead A narrow line of weld metal or sealant; a strip of metal or wood used to hold a sheet of glass in place; a narrow, convex molding profile; a metal edge or corner accessory for plaster.

Beam A linear or curved structural member that acts primarily to resist nonaxial loads.

Beam blank *See* **bloom**.

Bearing A point at which one building element rests upon another.

Bearing block A piece of wood fastened to a column to provide support for a beam or girder.

Bearing pad A block of plastic or synthetic rubber used to cushion the point at which one precast concrete element rests upon another.

Bearing wall A wall that carries structural loads from floors, roofs, or walls above.

Bed *See* **casting bed**.

Bed joint The horizontal layer of *mortar* beneath a masonry unit.

Bedrock A solid stratum of rock.

Bending moment The combination of tension and compression forces that cause a beam or other structural member to bend. *See also* **moment**.

Bending stress A compressive or tensile stress resulting from the application of a nonaxial force to a structural member.

Bent A plane of framing consisting of beams and columns joined together, often with rigid joints.

Bentonite clay A colloidal clay that swells to several times its dry volume when saturated with water; the primary ingredient in bentonite waterproofing.

Bessemer process An early method of steel manufacturing in which air was blown into a vessel of molten iron to burn out impurities.

Bevel An end or edge that is cut at other than a right angle.

Bevel siding Wood cladding boards that taper in cross section.

Billet A large cylinder or rectangular solid of material.

BIM *See* **building information modeling**.

Bio-based material A material produced through agricultural or animal biological processes.

Biodeterioration Mold, mildew, decay, and insect damage to wood; more generally, the degradation of material caused by biological organisms.

BIPV *See* **building-integrated photovoltaic**.

Birdsmouth cut An angled notch cut into a rafter to allow the rafter to seat securely on the top plate of a wall.

Bite The depth to which the edge of a piece of glass is held by its frame.

Bitumen A tarry mixture of hydrocarbons, such as asphalt or coal tar.

Bituminous roof membrane A *low-slope roof* membrane made from bituminous materials, either a *built-up roof membrane* or a *modified bitumen roof membrane*.

Blast furnace slag A hydraulic cementitious material formed as a byproduct of iron manufacture, used in mortar and concrete mixtures. Also called *slag cement*.

Blast-resistant glazing Window, storefront, or curtain wall systems designed for resistance to the force of explosive blasts.

Bleed water In freshly placed concrete, water that rises to the top surface of the concrete as the solid cement and aggregate particles settle.

Blended hydraulic cement Hydraulic cement made from a mixture of cementitious materials, such as portland cement, other hydraulic cements, and pozzolans, for the purpose of altering one or more properties of the cement or reducing the energy required in the cement manufacturing process.

Blind nailing Attaching boards to a frame, sheathing, or subflooring with toe nails driven through the edge of each piece so as to be completely concealed by the adjoining piece.

Blind-side waterproofing A water-impervious layer or coating on the outside of a foundation wall that, for reasons of inaccessibility, was installed before the wall was constructed.

Blocking Pieces of wood inserted tightly between joists, studs, or rafters in a building frame to stabilize the structure, inhibit the passage of fire, provide an attachment surface for finish materials, or retain insulation.

Bloom A rectangular solid of steel formed from an ingot as an intermediate step in creating rolled steel structural shapes.

Blooming mill A set of rollers used to transform an ingot into a bloom.

Bluestone A sandstone that is gray to blue-gray and splits readily into thin slabs; classified by ASTM C119 in the Quartz-Based Stone group.

Board A sawed wood member, rectangular in cross section, with a least nominal dimension of less than 2 inches (38 mm actual size). *See also* **dimension lumber**, **timber**.

Board foot A unit of lumber volume, nominally 12 square inches in cross-sectional area and 1 foot long.

Board siding Wood cladding made up of boards, as differentiated from *shingles* or manufactured wood panels.

Bolster A long chair used to support *reinforcing bars* in a concrete slab.

Bolt A fastener, usually metallic, consisting of a cylindrical body with a head at one end and a helical thread at the other, intended to be inserted through holes in adjoining pieces of material and closed with a threaded *nut*.

Bond In masonry, the adhesive force between mortar and masonry units, or the

pattern in which masonry units are laid to tie two or more wythes together into a structural unit. In reinforced concrete, the adhesion between the surface of a *reinforcing bar* and the surrounding concrete.

Bond breaker A strip of material to which *gunnable sealant* does not adhere.

Bond classification A system for rating the durability of a structural wood panel under conditions of repeated wetting or long-term weather exposure.

Bonded posttensioning A system of prestressing in which the tendons are grouted after stressing so as to bond them to the surrounding concrete.

Bottom bar A *reinforcing bar* that lies close to the bottom of a beam or slab.

Bottom plate *See* **sole plate**.

Bound water In wood, the water held within the cellulose of the cell walls. *See also* **free water**.

Box beam A bending member of metal or plywood whose cross section resembles a closed rectangular box.

Box girder A major spanning member of concrete or steel whose cross section is a hollow rectangle or trapezoid.

Box nail A nail with a slenderer shank than a *common nail*; used for fastening framing members in wood light frame construction.

Braced frame A structural building frame strengthened against lateral forces with diagonal members.

Bracing Diagonal members, either temporary or permanent, installed to stabilize a structure against lateral loads.

Brad A small *finish nail*.

Brake A machine used to form lengths of sheet metal into bent shapes.

Brake metal Sheet metal, formed into final shape using a *brake*.

Brazing A process that uses molten *nonferrous metal* to join two pieces of metal. The brazing metal is melted at a temperature below that of the metals being joined, so that, unlike in welding, the joined metals remain in a solid state throughout the process.

Breather mat A wiry plastic matting placed within a roof or wall assembly to create a space for drainage and ventilation.

Brick A hand-sized *masonry unit*, usually of fired *clay*.

Bridging Bracing or blocking installed between steel or wood joists at intermediate points to stabilize the joists against buckling and, in some cases, to permit adjacent joists to share loads.

British thermal unit (BTU) The quantity of heat required to raise the temperature of 1 pound of water 1 degree Fahrenheit.

Brittleness The measure of a materials tendency to fail without plastic deformation. The opposite of *ductility*.

Broom finish A skid-resistant texture imparted to an uncured concrete surface by dragging a stiff-bristled broom across it.

Brown coat The second of two base-coat plaster applications in a three-coat plaster.

Brownstone A brownish or reddish sandstone; classified by ASTM C119 in the Quartz-Based Stone group.

BTU *See* **British thermal unit**.

Buckling Structure failure by gross lateral deflection of a slender element under compressive stress, such as the sideward buckling of a long, slender column or the upper edge of a long, thin floor joist.

Building brick Brick used for concealed masonry work where appearance is not a concern.

Building code A set of regulations intended to ensure a minimum standard of health and safety in buildings.

Building enclosure The parts of the building, including its walls, roofs, floors, and fenestration, that separate the interior of the building from the exterior and that must effectively control the flow of heat, air, liquid water, and water vapor. Also called the *building envelope*.

Building envelope *See* **building enclosure**.

Building felt *See* **asphalt-saturated felt**.

Building information modeling (BIM) The digital, three-dimensional modeling of building systems, with the linking of model components to a database of properties and relationships.

Building-integrated photovoltaic (BIPV) Conventional building materials laminated or coated with *photovoltaic* materials and interconnected into a power-generating array.

Building paper A water-resistive, asphalt-saturated paper used similarly to *asphalt-saturated felt* to provide a protective layer in an exterior wall assembly.

Building separation joint A plane along which a building is divided into separate structures that may move independently of one another.

Built-up roof (BUR) A multi-ply roof membrane made from layers of asphalt-saturated felt or other fabric bonded together with bitumen.

Bull float A long-handled tool used for the initial floating of a freshly poured concrete slab. *See also* **darby**.

BUR *See* **built-up roof**.

Butt The thicker end, such as the lower edge of a wood shingle or the lower end of a tree trunk; a joint between square-edged pieces; a weld between square-edged pieces of metal that lie in the same plane; a type of door hinge that attaches to the edge of the door.

Butt-joint glazing A type of glass installation in which the vertical joints between lites of glass do not meet at a mullion, but are made weathertight with a sealant.

Button head A smooth, convex bolt head with no provision for engaging a wrench.

Buttress A structural device, usually of masonry or concrete, that resists the diagonal forces from an arch or vault.

Butyl rubber A synthetic rubber compound.

C

CAC *See* **Ceiling Attenuation Class**.

CAD *See* **computer-aided design**.

Caisson A cylindrical sitecast concrete foundation unit that penetrates through incompetent soil to rest upon an underlying stratum of rock or satisfactory soil; an enclosure that permits excavation work to be carried out underwater. Also called a *drilled pier*.

Calcined gypsum Gypsum that has been ground to a fine powder and heated to drive off most of its water of hydration; used in the manufacture of gypsum board and as the principal ingredient in gypsum plasters; a nonhydraulic cementitious material. Also called *plaster of Paris*.

Calcining The driving off of the water of hydration from gypsum by the application of heat.

Camber A slight, intentional initial curvature in a beam or slab.

Cambium The thin layer beneath the bark of a tree that manufactures cells of wood and bark.

Cantilever A beam, truss, or slab that extends beyond its last point of support.

Cant strip A strip of material with a sloping face used with multi-ply roof membranes to ease transitions from horizontal to vertical surfaces.

Capillary action The pulling of water through a small orifice or fibrous material by the attractive force between the water and the material.

Capillary break A slot or groove intended to create an opening too large to be bridged by a drop of water and, thereby, to eliminate the passage of water by *capillary action*; the coarse aggregate layer under a concrete slab on grade that discourages the migration of water from the ground below into the concrete slab above.

Carbonation The process by which lime mortar reacts with atmospheric carbon dioxide to cure.

Carbon fiber reinforcing In precast concrete, an open grid fabric of carbon fibers bonded with epoxy resin, used as a substitute for *welded wire reinforcing*.

Carbon sequestration In wood, the capture of atmospheric carbon dioxide and its conversion and storage as carbohydrates in living trees and wood construction products.

Carbon steel Low-carbon or *mild steel*.

Carbon steel bolt A relatively low-strength bolt most often used for fastening minor steel framing elements or temporary connections.

Carpenter One who makes things of wood.

Casement window A window that pivots on an axis at or near a vertical edge of the sash.

Casing The wood finish pieces surrounding the frame of a window or door; a cylindrical steel tube used to line a drilled or driven hole in foundation work.

Castellated beam A steel wide-flange section whose web has been cut along a zigzag path and reassembled by welding in such a way as to create a deeper section.

Casting Pouring a liquid material or slurry into a mold whose form it will take as it solidifies.

Casting bed A permanent, fixed form in which precast concrete elements are produced.

Cast-in-place concrete Concrete that is poured in its final location; *see also* **sitecast concrete**.

Cast iron Iron with too high a carbon content to be classified as steel.

Cathode The metal in a *galvanic couple* that experiences a decreased rate of corrosion.

Caulk A low-range *sealant*.

Cavity drainage material *See* **mortar deflection material**.

Cavity wall A masonry wall that includes a continuous, vertical hollow space between its outermost wythe and the remainder of the wall, primarily for the purpose of controlling water ingress.

Cee A metal framing member whose cross-sectional shape resembles the letter *C*.

Ceiling Attenuation Class (CAC) An index of the ability of a ceiling construction to obstruct the passage of sound between rooms through the plenum.

Ceiling joist *See* **joist**.

Cellular decking Panels made of steel sheets corrugated and welded together in such a way that hollow longitudinal cells are created within the panels.

Cellular raceway A rectangular tube cast into a concrete floor slab for the purpose of housing electrical and communications wiring.

Cellulose A complex polymeric carbohydrate of which the structural fibers in wood are composed.

Celsius A temperature scale on which the freezing point of water is established as 0 and the boiling point as 100 degrees.

Cement In concrete, masonry, and plastering work, any of a number of inorganic materials that have cementing properties when combined with water; more generally, any substance used to adhere material together. *See also* **cementitious materials**.

Cementitious materials In concrete, masonry, and plastering, inorganic materials that, when mixed with water, produce hardened products with adhesive and cohesive (cementing) properties; frequently used to refer exclusively to hydraulic cements (such as portland cement), to the exclusion of nonhydraulic (lime and gypsum) cements.

Cement–lime mortar Mortar made from portland cement, hydrated lime, aggregate, and water, the most traditional formulation of modern masonry mortars. *See also* **masonry cement, mortar cement**.

Centering Temporary formwork for an arch, dome, or vault.

Centering shims Small blocks of synthetic rubber or plastic used to hold a sheet of glass in the center of its frame.

Ceramic tile Small, flat, thin, fired clay tiles intended for use as wall and floor facings.

Chair A device used to support *reinforcing bars*.

Chamfer A flattening of a longitudinal edge of a solid member on a plane that lies at an angle of 45 degrees to the adjoining planes.

Channel A steel or aluminum section shaped like a rectangular box with one side missing.

Chemically strengthened glass Glass strengthened by immersion in a molten salt bath, causing an ion exchange at the surfaces of the glass that creates a prestress in a manner similar to *heat-treated glass*.

Chord A top or bottom member of a truss.

Chromogenic glass Glass that can change its optical properties, such as *thermochromic, photochromic*, and *electrochromic glass*.

C–H stud A steel wall framing member whose profile resembles a combination of the letters *C* and *H;* used to support gypsum panels in shaft walls.

Chuck A device for holding a steel wire, rod, or cable securely in place by means of steel wedges in a tapering cylinder.

Churn drill A steel tool used with an up-and-down motion to cut through rock at the bottom of a steel pipe caisson.

Cladding A material used to cover the exterior of a building.

Clamp A tool for holding two pieces of material together temporarily; unfired bricks piled in such a way that they can be fired without using a kiln.

Class A, B, C roofing Roof covering materials classified according to their resistance to fire when tested in accordance with ASTM E108. Class A is the most resistant, and Class C is the least.

Clay A fine-grained soil with plate-shaped particles, typically less than 0.0002 inch (0.005 mm) in size, whose properties are significantly influenced by the structural arrangements of the particles and the electrostatic forces acting between them.

Cleanout hole An opening at the base of a masonry wall through which mortar droppings and other debris can be removed before the interior cavity of the wall is grouted.

Clear dimension, clear opening The dimension between opposing inside faces of an opening.

Cleavage membrane A resilient sheet placed underneath a finish tile assembly

to prevent movement stresses in the underlying substrate from telegraphing into the finish assembly.

Climbing crane A heavy-duty lifting machine that raises itself as the building rises.

Clinker A fused, pebblelike mass that is an intermediate product of cement manufacture; a brick that is overburned.

Closer The last masonry unit laid in a course; a partial masonry unit used at the corner of a header course to adjust the joint spacing; a mechanical device for regulating the closing action of a door.

CLSM *See* **controlled low-strength material**.

CLT *See* **cross-laminated timber**.

CMU *See* **concrete masonry unit**.

Coarse aggregate Gravel or crushed stone in a concrete mix.

Coarse-grained soil Soil with particles ranging in size from roughly 0.003 to 3 inches (0.075 to 75 mm); sands and gravels.

Code *See* **building code**.

Coefficient of friction A unitless measure of the resistance to slippage between two surfaces, either at rest (*static coefficient of friction*) or in motion (*dynamic coefficient of friction*) relative to each other. A higher value represents greater slip resistance. Used to describe the slip resistance of some finish flooring materials.

Cohesionless soil *See* **frictional soil**.

Cohesive soil A soil such as clay whose particles are able to adhere to one another by means of cohesive and adhesive forces.

Cold-formed steel Steel formed at a temperature at which it is no longer plastic, as by rolling or forging at room temperature.

Cold-rolled steel Steel rolled to its final form at a temperature at which it is no longer plastic.

Cold-worked steel *See* **cold-formed steel**.

Collar joint The vertical mortar joint between wythes of masonry.

Collar tie A piece of wood nailed across two opposing rafters near the ridge to resist wind uplift.

Collated nails Nails glued together in a strip for insertion into a nail gun.

Collector A framing component that transfers lateral forces into parts of the structure designed to resist those forces.

Column An upright structural member acting primarily in compression.

Column bar *See* **vertical bar**.

Column cage An assembly of vertical *reinforcing bars* and *ties* for a concrete column.

Column-cover-and-spandrel system A system of cladding in which panels of material cover the columns and spandrels, with horizontal strips of windows filling the remaining portion of the wall.

Column spiral A continuous coil of steel reinforcing used to tie a concrete column.

Column tie A single loop of steel bar, usually bent into a rectangular configuration, used to tie a concrete column.

Combination door A door with interchangeable inserts of glass and insect screening, usually used as a second, exterior door and mounted in the same opening with a conventional door.

Commercial wrap A synthetic sheet material, heavier than *housewrap*, with water-resistive and air-resistive properties used to provide a protective layer in an exterior wall assembly.

Common bolt *See* **carbon steel bolt**.

Common bond Brickwork laid with five courses of stretchers followed by one course of headers.

Common nail A standard-sized nail used for the fastening of rough framing members in wood light frame construction.

Common rafter A roof *rafter* that runs parallel to the main slope of the roof. *See also* **hip rafter**.

Composite A material or assembly made up of two or more materials bonded together to act as a single unit.

Composite column An upright structural member, acting primarily in compression, that is composed of concrete and a steel structural shape, usually a wide flange or a tube.

Composite construction An assembly of differing materials, such as concrete and steel or concrete and wood, that once assembled is capable of performing as a unified structural unit.

Composite masonry wall A multi-wythe masonry wall in which the wythes are bonded one to another and act as a unified mass; a solid masonry wall that combines masonry units of different types.

Composite metal decking Corrugated steel decking manufactured in such a way that it bonds securely to the concrete fill to form a reinforced concrete deck.

Composition shingle *See* **asphalt shingle**.

Compression A squeezing force.

Compression gasket A synthetic rubber strip that seals around a sheet of glass or a wall panel by being squeezed tightly against it.

Compressive strength The ability of a material to withstand squeezing forces.

Compressive stress Internal *stress*, caused by squeezing a material.

Computer-aided design (CAD) The digital two-dimensional representation of building systems.

Concave joint A mortar joint tooled into a curved, indented profile.

Concealed flashing *See* **internal flashing**.

Concealed grid A suspended ceiling framework that is completely hidden by the tiles or panels it supports.

Concrete A structural material produced by mixing predetermined amounts of cement, aggregates, and water and allowing this mixture to cure under controlled conditions.

Concrete admixture *See* **admixture**.

Concrete block A *concrete masonry unit*, usually hollow, that is larger than a brick.

Concrete masonry unit (CMU) A block of hardened *concrete*, with or without hollow cores, designed to be laid in the same manner as a brick or stone; a concrete block.

Condensate Water formed as a result of *condensation*.

Condensation The process of changing from a gaseous to a liquid state, especially as applied to water.

Conduction *See* **thermal conduction**.

Conduit A steel or plastic tube through which electrical wiring is run.

Consolidate In freshly poured concrete, to eliminate trapped air and cause the concrete to fill completely around the reinforcing bars and into all the corners of the formwork; usually done by vibrating the concrete.

Construction documents The graphic *construction drawings* and written *specifications* to which a building is constructed.

Construction drawings The graphic portion of the *construction documents*, usually produced by an architect or engineer, concerning the construction of a building.

Construction manager An entity that assists the owner in the procurement of construction services.

Construction type In the International Building Code, any of five major systems of building construction that are differentiated by their relative resistance to fire.

Continuous insulation Insulation added to one side or the other of a framed wall, to reduce heat losses caused by thermal bridging of the wall studs and other framing components.

Contraction joint *See* **control joint**.

Contractor A person or organization that undertakes a legal obligation to do construction work.

Control joint An intentional, linear discontinuity in a structure or component designed to form a plane of weakness where cracking can occur in response to various forces so as to minimize or eliminate cracking elsewhere. Also called a *contraction joint*.

Controlled low-strength material (CLSM) A concrete that is purposely formulated to have a very low but known strength; used primarily as a *backfill* material.

Convection *See* **thermal convection**.

Convector A heat exchange device that uses the heat in steam, hot water, or an electric resistance element to warm the air in a room; often called, inaccurately, a *radiator*.

Cool color A coating applied to a roofing material that is nonwhite, yet reflects a relatively high percentage of the sun's thermal energy.

Cool roof A roof covering that reflects a substantial portion of the sun's thermal energy.

Cope The removal of a flange at the end of a steel beam in order to facilitate connection to another member; cutting of the end of a wood trim to match the profile of the piece with which it intersects.

Coped connection A joint in which the end of one member is cut to match the profile of the other member.

Coping A protective cap on the top of a masonry wall.

Coping saw A handsaw with a thin, narrow blade, used for cutting detailed shapes in the ends of wood moldings and trim.

Copolymer A large molecule composed of repeating patterns of two or more chemical units.

Copper A soft *nonferrous metal*, orange-red in original color, that oxidizes to a color ranging from blue-green to black.

Corbel A spanning device in which masonry units in successive courses are cantilevered slightly over one another; a projecting bracket of masonry or concrete.

Core structure A building structure in which lateral stability is provide by one or more stiffened vertical cores.

Corner bead A metal or plastic strip used to form a neat, durable edge at an outside corner of two walls of plaster or gypsum board.

Cornice The exterior detail at the meeting of a wall and a roof overhang; a decorative molding at the intersection of a wall and a ceiling.

Corrosion Oxidation, such as rust.

Corrosion inhibitor A concrete, mortar, or plaster admixture intended to prevent oxidation of *steel reinforcing bars*.

Corrugated Formed into a fluted or ribbed profile.

Counterflashing A flashing turned down from above to overlap another flashing turned up from below so as to shed water.

Course A horizontal layer of masonry units one unit high; a horizontal line of shingles or siding.

Coursed In masonry, laid in courses with straight bed joints.

Cove base A flexible strip of plastic or synthetic rubber used to finish the junction between resilient flooring and a wall.

Cover In concrete, a specified thickness of concrete surrounding *reinforcing bars* to provide full embedment for the bars and protect them against fire and corrosion.

Coverboard A material installed over low-slope roof insulation to protect the insulation, provide a more stable substrate for the roof membrane, or increase the fire resistance of the roof assembly.

Cradle-to-gate analysis A *life-cycle analysis* extending from resource extraction only so far as to when the material or product leaves its place of manufacture.

Cradle-to-grave analysis *See* **life-cycle analysis**.

Crawlspace A space that is not tall enough to stand in, located beneath the bottom floor of a building.

Creep A permanent inelastic deformation in a material caused by the prolonged application of a structural stress; common in wood, concrete, and plastics.

Cripple stud A wood wall framing member that is shorter than full-length studs because it is interrupted by a header or sill.

Critical path The sequence of tasks that determines the least amount of time in which a construction project can be completed.

Cross-grain wood Wood incorporated into a structure in such a way that the direction of its grain is perpendicular to the direction of the principal loads on the structure.

Cross-laminated timber (CLT) *Mass timber* panels fabricated from solid lumber, with the orientation of members alternating between layers; used as structural floor, wall, and roof elements.

Crosslot bracing Horizontal compression members running from one side of an excavation to the other, used to support sheeting.

Crown glass Glass sheet formed by spinning an opened hollow globe of heated glass.

Cruck A framing member cut from a bent tree so as to form one-half of a rigid frame.

Cup A curl in the cross section of a board or timber caused by unequal shrinkage or expansion between one side of the board and the other.

Curing The hardening of concrete, plaster, gunnable sealant, or other wet materials. Curing can occur through evaporation of water or a solvent, hydration, polymerization, or chemical reactions of various types, depending on the formulation of the material.

Curing compound A liquid that, when sprayed on the surface of newly placed concrete, forms a water-resistant layer to prevent premature dehydration of the concrete.

Curtain wall An exterior building wall that is supported by the frame of the building, rather than being self-supporting or loadbearing.

Cutoff wall An excavation support system that excludes groundwater from the excavation, eliminating the need for extensive dewatering.

Cylinder glass Glass sheet produced by blowing a large, elongated glass cylinder, cutting off its ends, slitting it lengthwise, and opening it into a flat rectangle.

D

d *See* **penny**.

Damage weighted transmittance (Tdw) The ratio of solar radiation that passes through a glazing unit to the amount of light striking the unit, weighted to account for the relative fading damage potential of the various wavelengths. The lower the damage weighted transmittance, the better the protection against fading afforded to interior fabrics and materials.

Damper A flap to control or obstruct the flow of gasses; specifically, a metal control flap in the throat of a fireplace or in an air duct.

Damping The addition of energy-absorbing components into a structural building frame, to reduce lateral deflections and lessen the stresses imparted into the frame when subjected to high wind or seismic forces.

Dampproofing A coating intended to resist the passage of water, commonly applied to the outside face of basement walls or to the inner face of a cavity in a masonry cavity wall.

Dap A notch at the end of a piece of material.

Darby A stiff straightedge of wood or metal used to level the surface of wet plaster or concrete.

Daylighting Illuminating the interior of a building by natural means.

DCOF *See* **dynamic coefficient of friction**.

Dead load Permanent loads on a building, including the weight of the building itself and any permanently attached equipment.

Decking A material used to span across beams or joists to create a floor or roof surface.

Deep foundation A building *foundation* that extends through upper strata of incompetent soil to reach deeper strata with greater bearing capacity.

Deflection track A special type of head track or runner used in light gauge steel framing to isolate partition framing from movements in the structure above. Also called a *slip track*.

Deformation A change in the shape of a structure or structural element caused by a load or force acting on the structure.

Deformed reinforcing bar A *steel reinforcing bar* with surface ribs for better bonding to concrete.

Demand-critical weld A structural steel connection weld, essential to the stability of the structure during a seismic event and subject to special quality control and inspection procedures during construction.

Depressed strand A pretensioning tendon that is pulled to the bottom of the beam at the center of the span to follow more closely the path of tensile forces in the member.

Derrick Any of a number of devices for hoisting building materials on the end of a rope or cable.

Design/bid/build project delivery A method of providing design and construction services in which the design and construction phases of the project are provided by different entities, usually used in combination with *sequential construction*.

Design/build project delivery A method of providing design and construction services in which the design and construction phases of the project are provided by a single entity; frequently used in combination with *fast track construction*.

Dewatering The extraction of water from an excavation or its surrounding soil.

Dew point The temperature at which water will begin to condense from a mass of air with a given moisture content.

Diagonal bracing *See* **bracing**.

Diamond saw A tool with a moving chain, belt, wire, straight blade, or circular blade whose cutting action is carried out by diamonds.

Diaphragm action A bracing action that derives from the stiffness of a thin plane of material when it is loaded in a direction parallel to the plane. Diaphragms in buildings are typically floor, wall, or roof surfaces of plywood, reinforced masonry, steel decking, or reinforced concrete.

Die An industrial tool for giving identical form to repeatedly produced or continuously generated units, such as a shaped orifice for giving form to a column of clay, a steel wire, or an aluminum extrusion; a shaped punch for making cutouts of sheet metal or paper; or a mold for casting plastic or metal.

Die-cut Manufactured by punching from a sheet material.

Differential settlement Subsidence of the various foundation elements of a building at differing rates.

Diffuser A louver shaped so as to distribute air about a room.

Diffusion *See* **water vapor diffusion**.

Dimension lumber A sawed wood member, rectangular in cross section, with a least nominal dimension between 2 and 4 inches (38 and 89 mm actual size). *See also* **board**, **timber**.

Dimension stone Building stone cut to a rectangular shape.

Direct tension indicator washer *See* **load indicator washer**.

Distribution rib A transverse beam at the midspan of a one-way concrete joist structure, used to allow the joists to share concentrated loads.

Divider strip A strip of metal or plastic embedded in terrazzo to form control joints and decorative patterns.

DLT *See* **dowel-laminated timber**.

Dome An arch rotated about its vertical axis to produce a structure shaped like an inverted bowl; a form used to make one of the cavities in a concrete waffle slab.

Dormer A structure protruding through the plane of a sloping roof, usually containing a window and having its own smaller roof.

Double glazing Two parallel sheets of glass with an airspace between.

Double-hung window A window with two overlapping sashes that slide vertically in tracks.

Double shear Acting to resist shear forces at two locations, such as a bolt that passes through a steel supporting angle, a beam web, and another supporting angle.

Double-skin facade An exterior wall system consisting of two separate glass skins separated by an interstitial space.

Double-strength glass Glass that is approximately $\frac{1}{8}$ inch (3 mm) thick.

Double tee A precast concrete slab element that resembles the letters *TT* in cross section.

Dovetail slot anchor A system for fastening to a concrete structure that uses metal tabs inserted into a slot that is small at the face of the concrete and larger behind.

Dowel A short cylindrical rod of wood or steel; a *steel reinforcing bar* that projects from a foundation to tie it to a column or wall, or from one section of a concrete slab or wall to another.

Dowel-laminated timber (DLT) *Mass timber* panels fabricated from solid lumber aligned side-by-side and joined with hardwood dowels; used as structural floor, wall, and roof elements.

Downspout A vertical pipe for conducting water from a roof to a lower level. Also called a *leader*.

Drag strut A framing member or component acting as a *collector* to transfer lateral forces within the building frame. Also called a *drag tie*.

Drainage Removal of water.

Drainage fill Crushed stone or gravel backfill materials with good drainage characteristics, placed around a foundation to facilitate drainage.

Drained cladding An exterior wall assembly consisting of cladding, a drainage space, and an *air and water-resistive barrier*, designed to control the passage of water through the wall. Also called *rainscreen cladding*.

Draped tendon A posttensioning strand placed along a curving profile that approximates the path of the tensile forces in a beam.

Drawing Shaping a material by pulling it through an orifice, as in the drawing of steel wire or the drawing of a sheet of glass.

Drawings *See* **construction drawings**.

Drawn glass Glass sheet pulled directly from a container of molten glass.

Drift Lateral deflection of a building caused by wind or earthquake loads.

Drift pin A tapered steel rod used to align bolt holes in steel connections during erection.

Drilled pier *See* **caisson**.

Drip A discontinuity formed into the underside of a windowsill or wall component to force adhering drops of water to fall free of the face of the building rather than to move farther toward the interior.

Dropchute A flexible hoselike tube for placing concrete; used to break the fall of the concrete and prevent *segregation*.

Drop panel A thickening of a two-way concrete structure at the head of a column.

Drying shrinkage Shrinkage of concrete, mortar, or plaster that occurs as excess water evaporates from the material.

Dry-pack grout A low-slump cementitious mixture tamped into the space in a connection between precast concrete members.

Dry-press process A method of molding slightly damp clays and shales into bricks by forcing them into molds under high pressure.

Dry-set mortar A tile-setting mortar formulated with portland cement, sand, and water retention compounds; used in thin-set tile applications.

Dry systems Systems of construction that use little or no water during construction, as differentiated from systems such as masonry, plastering, and ceramic tile work.

Drywall *See* **gypsum board**.

Dry well An underground pit filled with broken stone or other porous material from which rainwater from a roof drainage system can seep into the surrounding soil.

Duct A hollow conduit, commonly of sheet metal, through which air can be circulated; a tube used to establish the position of a posttensioning tendon in a concrete structure.

Ductility The measure of a material's ability to undergo plastic deformations outside of its elastic range, without failure. May refer specifically to a material's behavior under tensile stress, or may be applied more broadly to structural connections or members designed to withstand plastic extension and compression. The opposite of *brittleness*.

DWV pipe Drain–waste–vent pipe; the part of the plumbing system of a building that removes liquid wastes and conducts them to the sewer or sewage disposal system.

Dynamic coefficient of friction (DCOF) The *coefficient of friction*, measured between two surfaces in motion relative to each other; used in some finish flooring slip resistance measurements. *See also* **static coefficient of friction**.

E

Earlywood *See* **springwood**.

Earth material Rock or soil.

Eave The horizontal edge at the low side of a sloping roof.

ECC *See* **engineered cementitious composite**.

Ecolabel Third-party environmental rating of a building material or product.

Edge bead A strip of metal or plastic used to make a neat, durable edge where plaster or gypsum board abuts another material.

Edge spacer The material used to separate lites of glass in an insulating glass unit. Also called a *spline*.

Efflorescence A light-colored, powdery deposit on the face of masonry or concrete, caused by the leaching of chemical salts from water migrating from within the structure to the surface.

Egress system *See* **means of egress**.

EIFS *See* **exterior insulation and finish system**.

Elastic Able to return to its original size and shape after removal of stress.

Elastomer A synthetic rubber.

Elastomeric With rubberlike properties.

Electrochromic glass Glass that changes its optical properties in response to the application of electric current.

Electrode A consumable steel wire or rod used to maintain an arc and furnish additional weld metal in electric arc welding.

Electrogalvanizing A method of *galvanizing*, in which an electric current is used to deposit zinc from a liquid bath onto steel.

Elevation A drawing that views a building from any of its sides; a vertical height above a reference point, such as sea level.

Elongation Stretching under load; growing longer because of temperature expansion.

Embodied carbon The total carbon emissions associated with a material or product throughout its life cycle.

Embodied energy The total energy consumption associated with a material or product throughout its life cycle.

Embodied water The total freshwater consumption associated with a material or product throughout its life cycle.

EMC *See* **equilibrium moisture content**.

Enamel A glossy or semigloss paint.

End dam The turned-up end of a flashing that prevents water from running out of the end; a block inserted into the space within a horizontal aluminum mullion for the same purpose.

End nail A nail driven through the side of one piece of lumber and into the end of another.

Energy recovery ventilator A mechanical device that exhausts air from a building while recovering much of the sensible and latent heat from the exhausted air

and transferring it to the incoming air. *See also* **heat recovery ventilator**.

Engineered cementitious composite (ECC) A concrete with high tensile strength and *ductility*, formulated from polymer fiber-reinforcing, cementitious materials and fine aggregate.

Engineered fill Earth compacted into place in such a way that it has predictable physical properties, based on laboratory tests and specified, supervised installation procedures.

Engineered lumber *See* **structural composite lumber**.

English bond Brickwork laid with alternating courses, each consisting entirely of headers or stretchers.

EPDM Ethylene propylene diene monomer, a synthetic rubber thermosetting material used in low-slope roofing membranes.

Equilibrium moisture content (EMC) The moisture content at which wood stabilizes after a period of time in its destination environment.

Erector The subcontractor who raises, connects, and plumbs up a building frame from fabricated steel or precast concrete components.

ETFE *See* **ethylene tetrafluoroethylene**.

Ethylene propylene diene monomer *See* **EPDM**.

Ethylene tetrafluoroethylene (ETFE) A thin, extruded polymer film used in fabric structures and lightweight, transparent or translucent building enclosures.

Expanded metal lath A thin sheet of metal that has been slit and stretched to transform it into a mesh; used as a base for the installation of plaster.

Expanded shale aggregate A *structural lightweight aggregate* made from ground shale particles that have been heated to the point that moisture within the particles vaporizes, causing the particles to expand.

Expansion joint A seam within a material or between materials that provides for material expansion and contraction.

Expansive soil A clay soil that expands significantly with increased moisture content.

Exposed aggregate finish A concrete surface in which the coarse aggregate is revealed.

Exposed grid A framework for an acoustical ceiling that is visible from below after the ceiling is completed.

Extended-life admixture A substance that retards the onset of the curing reaction in mortar so that the mortar may be used over a protracted period of time after mixing.

Extended set-control admixture A substance that retards the onset of the curing reaction in concrete so that the material may be used over a protracted period of time after mixing.

Extensive green roof A *green roof* with a relatively shallow soil, planted with low-maintenance, drought-tolerant plant materials.

Exterior insulation and finish system (EIFS) A cladding system that consists of a reinforced stucco applied directly to the surface of an insulating foam board.

External flashing In masonry, a *flashing* that is not concealed within the wall, usually at the roof level or top of the wall.

External gutter A *gutter* hung off the edge of a roof, external to the roof construction itself.

Extrados The convex surface of an arch.

Extrusion The process of forcing a material through a shaped orifice to produce a linear element with the desired cross section; an element produced by this process.

F

Fabricator The entity that prepares structural steel members for erection; any entity that assembles building components prior to arrival of the components on the construction site.

Façade An exterior face of a building.

Face brick A brick selected on the basis of appearance and durability for use in the exposed surface of a wall.

Face nail A nail driven through the side of one wood member into the side of another.

Face-sealed wall *See* **barrier wall**.

Face shell The portion of a hollow concrete masonry unit that forms the face of the wall.

Fahrenheit A temperature scale on which the boiling point of water is fixed at 212 degrees and the freezing point at 32 degrees.

Fanlight A semicircular or semielliptical window above an entrance door; often includes radiating muntins that resemble a fan.

Fascia The exposed vertical face of an *eave*.

Fast track construction A method of providing design and construction services in which design and construction overlap in time. Also called *phased construction*.

Faying surface The contacting surfaces of steel members joined with a *slip-critical connection*.

Felt A thin, flexible sheet material made of fibers of paper, glass, or plastic pressed and bonded together.

Ferrous metal Any iron-based metal.

Ferrous steel In common usage, steel unprotected from corrosion by either galvanizing or alloying.

Fibrous reinforcing Short fibers of glass, steel, or polypropylene mixed into concrete to act as either *microfiber reinforcing* or *macrofiber reinforcing*.

Field Impact Isolation Class (FIIC) An *Impact Isolation Class* rating based on measurements taken in the finished construction, rather than in the laboratory.

Field Sound Transmission Class (FSTC) A *Sound Transmission Class* rating based on measurements taken in the finished construction according to ASTM E336, rather than in the laboratory.

Fieldstone Rough building stone gathered from riverbeds and fields.

Figure The surface pattern of the grain of a piece of smoothly finished wood or stone.

FIIC *See* **Field Impact Isolation Class**.

Filigree precast concrete A hybrid concrete system in which *precast concrete* sections are used as *permanent formwork* for *cast-in-place* concrete.

Fillet A rounded inside intersection between two surfaces that meet at an angle.

Fillet weld A weld at the inside intersection of two metal surfaces that meet at right angles.

Fine aggregate Sand used in concrete, mortar, or plaster mixes.

Fine-grained soil Soil with particles 0.003 inch (0.075 mm) or less in size; silts and clays.

Finger joint A glued end connection between two pieces of wood, using an interlocking pattern of deeply cut "fingers." A finger joint creates a large surface for the glue bond, to allow it to develop the full tensile strength of the wood it connects.

Finial A slender ornament at the top of a roof or spire.

Finish Exposed to view; material that is exposed to view; final, exposed coating or surface treatment of a material.

Finish carpenter One who does *finish carpentry*.

Finish carpentry The wood components exposed to view on the building and usually assembled on site, such as window and door casings, baseboards, bookshelves, and the like; may also refer to exterior finish carpentry, such as exterior trim, deck railings, and similar items.

Finish coat The final coat of paint, plaster, or other finishing system.

Finish-coat plaster The final coat of plaster, applied over gypsum base or one or more applications of *base-coat plaster*.

Finish floor The floor material exposed to view, as differentiated from the *subfloor*, which is the loadbearing floor surface beneath.

Finish lime A fine grade of *quicklime* used in finish-coat gypsum plasters and in ornamental plaster work. Also called *lime putty*.

Finish nail A relatively thin nail with a very small head; used for fastening trim and other finish woodwork items.

Fire area In the International Building Code, an area within a building bounded by fire-resistant construction. Fire area size, occupant load, and location within the building are used to determine automatic sprinkler requirements.

Fire barrier In the International Building Code, a fire-resistant wall intended to deter the spread of fire; used to separate exit stair enclosures, differing occupancies, and fire areas.

Fireblocking Wood or other material used to partition concealed spaces within combustible framing; intended to restrict the spread of fire within such spaces.

Firebox The part of a fireplace, stove, or furnace in which fuel is combusted.

Firebrick A brick made to withstand very high temperatures, as in a fireplace, furnace, or industrial chimney.

Firecut A sloping end cut on a wood beam or joist where it enters a masonry wall. The purpose of the firecut is to allow the wood member to rotate out of the wall without prying the wall apart if the floor or roof structure burns through in a fire.

Fire door A fire-resistant door, used in fire-resistance-rated partitions and walls.

Fire partition In the International Building Code, a fire-resistant wall intended to deter the spread of fire; used to separate tenant spaces, dwelling units, and corridors from surrounding areas of a building.

Fireproofing Material used around steel or concrete structural elements to insulate them against excessive temperatures in case of fire.

Fire-protection-rated glazing *Fire-rated glass* for use in fire doors, fire windows, and other protected openings. *See also* **fire-resistance-rated glazing**.

Fire-rated glass Glass that is capable of retaining its integrity after being exposed to fire, either *fire-protection-rated glazing* or *fire-resistance-rated glazing*.

Fire-resistance-rated glazing *Fire-rated glass* capable of substituting in full for solid, fire-resistance rated wall assemblies. Unlike *fire-protection-rated glazing*, fire-resistance-rated glazing is not limited to use in doors, windows, and other openings.

Fire resistance-rating The time, in minutes or hours, that a material or assembly will resist fire exposure as determined by ASTM E119.

Fire safing Fire-resistant material inserted into a space between a curtain wall and a spandrel beam or column to retard the passage of fire from one floor to the next.

Firestopping Materials installed in an opening through a fire-rated wall or floor-ceiling assembly to retard the passage of smoke and fire, and to maintain the fire-resistance performance of the assembly.

Fire wall A wall extending from foundation to roof, required under a building code to separate buildings, or parts of buildings, as a deterrent to the spread of fire.

Firing The process of converting dry clay into a ceramic material through the application of intense heat.

First cost The cost of construction, not including operational costs.

Fixed window Glass that is immovably mounted in a wall.

Flagstone Flat stones used for paving or flooring.

Flame-spread rating A measure of the rapidity with which fire will spread across the surface of a finish material as determined by ASTM standard E84.

Flange A projecting crosspiece of a wide-flange or channel profile; a projecting fin.

Flash cove A detail in which a sheet of resilient flooring is turned up at the edge and finished against the wall to create an integral baseboard.

Flashing A thin, continuous sheet of metal, plastic, rubber, or waterproof paper used to prevent the passage of water through a joint in a wall, roof, or chimney.

Flat glass Glass produced in flat sheets for architectural applications, usually by the float process. *See also* **float glass**.

Flat-grain lumber *See* **plainsawn lumber**.

Flat roof *See* **low-slope roof**.

Flat seam A sheet metal roofing seam that is formed flat against the surface of the roof.

Flemish bond Brickwork laid with each course consisting of alternating headers and stretchers.

Flitch A collection of solid wood members or veneers, all cut from a single log.

Float A small platform suspended on ropes from a steel building frame to permit ironworkers to work on a connection; a trowel with a slightly rough surface used in an intermediate stage of finishing a concrete slab; as a verb, to use a float for finishing concrete.

Float glass Glass sheet manufactured by cooling a layer of molten glass on a bath of molten tin.

Floating floor Wood or laminate flooring that is not fastened or adhered to the subfloor.

Floating foundation A *foundation* placed at depth such that the weight of the soil removed is approximately equal to the weight of the building being supported.

Flood test The submersion of a horizontal waterproofing system, usually for an extended period of time, to check for leaks.

Floor joist *See* **joist**.

Flue A passage for smoke and combustion products from a furnace, stove, water heater, or fireplace.

Fluid-applied roof membrane A roof membrane applied in one or more coats of a liquid that cure to form an impervious sheet.

Fluoropolymer A highly stable organic compound used as an exterior finish coating.

Flush Smooth, lying in a single plane.

Flush door A door with smooth planar faces.

Flush glazing *See* **structural glazing**.

Flux A material added to react chemically with impurities and remove them from molten metal. Fluxes are used both in steelmaking and in welding. Welding fluxes serve the additional purpose of shielding the molten weld metal from the air to reduce oxidation and other undesirable effects.

Fly ash Dust collected in the stacks of coal-fired power plants, used as a *supplementary cementitious material* in concrete and mortar.

Flying formwork Large sections of slab formwork that are moved by crane.

Fly rafter A *rafter* in a rake overhang.

F-number An index number expressing the statistical flatness or levelness of a concrete slab.

Foil-backed gypsum board *Gypsum board* with aluminum foil laminated to its back surface to act as a vapor retarder and thermal insulator.

Folded plate A roof structure whose strength and stiffness derive from a pleated or folded geometry.

Footing The part of a foundation that spreads a load from the building across a broader area of soil.

Forced-air system A furnace and/or cooling coil and ductwork that heat and/or cool air and deliver it, driven by a fan, to the rooms of a building.

Formaldehyde An organic compound known to cause a range of adverse human health effects, traditionally used in the manufacture of wood product adhesives and binders. *See also* **phenol-formaldehyde** and **urea-formaldehyde**.

Form deck Thin, corrugated steel sheets that serve as *permanent formwork* for a reinforced concrete deck.

Form release compound A substance applied to concrete formwork to prevent concrete from adhering.

Form tie A steel or plastic rod with fasteners on either end, used to hold together the two surfaces of formwork for a concrete wall.

Form-tie hole A depression, typically conical in shape, in a cast-in-place concrete wall that remains after the protruding portions of a form tie are removed.

Formwork Structures, usually temporary, that give shape to poured concrete and support it and keep it moist as it cures.

Foundation The portion of a building that transmits structural loads from the building into the earth.

Framed connection A *shear connection* between steel members made by means of steel angles or plates connecting to the web of the beam or girder.

Framing plan A diagram showing the arrangement and sizes of the structural members in a floor or roof.

Framing square An L-shaped measuring tool used by carpenters to lay out right-angle cuts as well as more complicated cuts, such as those required for stairs and sloping roof rafters.

Freestone Fine-grained sedimentary rock that has no planes of cleavage or sedimentation along which it is likely to split.

Free water In wood, water held within the cavities of the cells. *See also* **bound water**.

Freeze protection admixture A concrete or mortar additive used to allow curing under conditions of low ambient temperature.

Freeze-thaw weathering Erosion or fracturing that occurs when materials such as clay brick, concrete, and stone absorb moisture and then are subjected to cycles of freezing and thawing temperatures.

French door A symmetrical pair of glazed doors hinged to the jambs of a single frame and meeting at the center of the opening.

Frictional soil A soil, such as sand or gravel, that relies primarily on friction rather than attractive or repulsive forces between particles for its strength. Also called a *cohesionless soil*.

Friction-type connection *See* **slip-critical connection**.

Frit Ground-up colored glass that is heat-fused to lites of glass to form functional or decorative patterns.

Frost line The depth in the earth to which the soil can be expected to freeze during a severe winter.

FSTC *See* **Field Sound Transmission Class**.

Fully restrained moment connection A steel frame *moment connection* sufficiently rigid such that the geometric angles between connected pieces remain unchanged during normal loading.

Furring channel A sheet metal *furring strip* in the form of a C-channel.

Furring strip A length of wood or metal attached to a masonry or concrete wall to permit the attachment of finish materials using screws or nails; any linear material used to create a spatial separation between a finish material and an underlying substrate.

G

Gable The triangular wall beneath the end of a *gable roof*.

Gable roof A roof consisting of two oppositely sloping planes that intersect at a level ridge.

Gable vent A screened, louvered opening in a gable, used for exhausting excess heat and humidity from an attic.

Gage *See* **gauge**.

Galling Chafing or tearing of one material against another under extreme pressure.

Galvanic couple A pair of metals with differing electrochemical potential, between which electrical current will flow when the metals are placed in a conducting medium.

Galvanic series A list of metals in order of their relative electrochemical potential when immersed in a given conducting medium.

Galvanized steel Steel with a zinc coating for the purpose of providing protection from corrosion.

Galvanizing The application of a zinc coating to steel.

Gambrel A roof shape consisting of two superimposed levels of gable roofs with the lower level at a steeper pitch than the upper.

Gantt chart A graphic representation of a construction schedule, using a series of horizontal bars representing the duration of various tasks or groups of tasks that make up the project.

Gap graded soil A soil graded so as to contain a broad range of particle sizes, but with certain sizes omitted.

Gasket A dry, resilient material used to seal a joint between two rigid assemblies by being compressed between them.

Gauge A measure of the thickness of sheet material. Lower gauge numbers signify thicker sheets. Also spelled *gage*.

Gauged brick A brick that has been rubbed on an abrasive stone to reduce it to a trapezoidal shape for use in an arch.

Gauging plaster A gypsum plaster formulated for use in combination with finishing lime in finish coat plaster.

General contractor A construction entity with responsibility for the overall conduct of a construction project.

Geotextile A synthetic cloth used beneath the surface of the ground to stabilize soil or promote drainage.

GFRC *See* **glass-fiber-reinforced concrete**.

GFRP *See* **glass-fiber-reinforced plastic**.

Girder A horizontal beam that supports other beams; a very large beam, especially one that is built up from smaller elements.

Girt A horizontal beam that supports wall cladding between columns.

Glass block A hollow masonry unit made of glass.

Glass fiber batt A thick, fluffy, nonwoven insulating blanket of filaments spun from glass.

Glass-fiber-reinforced concrete (GFRC) Concrete with a strengthening admixture of short, alkali-resistant glass fibers.

Glass-fiber-reinforced plastic (GFRP) Plastic resin strengthened with embedded glass fibers, commonly referred to as "fiberglass."

Glass mullion system A method of constructing a large glazed area by stiffening the sheets of glass with perpendicular glass ribs.

Glass surface number A method of identifying the glass surfaces in any glazing unit, starting from the exterior side of the unit and working inward. For example, in a double-glazed unit, the outward facing surface of the outer lite is surface number 1. The inward facing surface of this lite is surface number 2. The outward and inward facing surfaces of the inner lite are surfaces number 3 and 4, respectively.

Glaze A glassy finish on a brick or tile; as a verb, to install glass.

Glazed structural clay tile A hollow clay block with glazed faces, usually used for constructing interior partitions.

Glazier One who installs glass.

Glazier's points Small pieces of metal driven into a wood sash to hold glass in place.

Glazing The act of installing glass; the transparent material (most often glass or plastic) in a glazed opening; as an adjective, referring to materials used in installing glass (for example, "glazing tape").

Glazing compound Any of several types of mastic used to bed small lites of glass in a frame.

Global warming potential A material or product's life-cycle contribution to global warming, caused by greenhouse gas emissions.

Glue-laminated wood A wood member made up of a large number of small strips of wood glued together.

Glulam A shorthand expression for glue-laminated wood.

Grade A classification of size or quality for an intended purpose; to classify as to size or quality.

Grade The surface of the ground; to move earth for the purpose of bringing the surface of the ground to an intended level or profile.

Grade beam A reinforced concrete foundation element that transmits the load from a bearing wall into spaced foundations such as pile caps or caissons.

Grain In wood, the direction of the longitudinal axes of the wood fibers or the figure formed by the fibers. In stone, *see* **quarry bed**.

Granite Igneous rock with visible crystals of quartz and feldspar.

Green building *See* **sustainability**.

Green roof A roof covered with soil and plant materials. Also called a *vegetated roof*.

Groove weld A weld made in a groove, created by beveling or milling the edges of the mating pieces of metal.

Ground A strip attached to a wall or ceiling to establish the level to which plaster should be applied.

Groundwater Water present in soils below the ground surface.

Grout A high-slump mixture of portland cement, fine aggregates, and water, which can be poured or pumped into cavities in concrete or masonry for the purpose of embedding *reinforcing bars* and/or increasing the amount of loadbearing material in a wall; a specially formulated mortarlike material for filling under steel baseplates and around connections in precast concrete framing; a mortar used to fill joints between ceramic tiles or quarry tiles.

Gunnable sealant A *sealant* material that is extruded in liquid or mastic form from a *sealant gun*.

Gusset plate A flat steel plate used to connect the members of a truss; a stiffener plate.

Gutter A horizontal or slightly sloped channel for the collection of rainwater and snowmelt at the eave of a roof.

GWB Gypsum wallboard; *see* **gypsum board**.

Gypsum An abundant mineral; chemically, hydrous calcium sulfate.

Gypsum backing board A lower-cost gypsum panel intended for use as an interior layer in multilayer constructions of gypsum board.

Gypsum board An interior-facing panel consisting of a gypsum core sandwiched between paper faces. Also called *drywall*, *plasterboard*.

Gypsum lath Sheets of gypsum board manufactured specifically for use as a plaster base.

Gypsum plaster Plaster whose cementing substance is calcined gypsum; used almost exclusively for interior finish plaster work.

Gypsum sheathing panel A water-resistant, gypsum-based sheet material used for exterior sheathing.

Gypsum wallboard (GWB) *See* **gypsum board**.

H

Hammerhead boom crane A heavy-duty lifting device that uses a tower-mounted horizontal boom that can rotate only in a horizontal plane.

Hardboard A very dense panel product, usually with at least one smooth face, made of highly compressed wood fibers.

Hardwood Wood from deciduous (broadleaf) trees.

Hawk A square piece of sheet metal with a perpendicular handle beneath used by a plasterer to hold a small quantity of wet plaster and transfer it to a trowel for application to a wall or ceiling.

HDO *See* **high-density overlay**.

Head The horizontal top portion of a window or door.

Header In framed construction, a member that carries other perpendicular framing members, such as a beam above an opening in a wall or a joist supporting other joists where they are interrupted by a floor opening. In steel construction, a beam that spans between girders. In masonry construction, a brick or other masonry unit that is laid across two wythes with its end exposed in the face of the wall.

Head jamb *See* **head**.

Head joint The vertical layer of mortar between ends of masonry units.

Hearth The noncombustible floor area outside a fireplace opening.

Heartwood The dead wood cells in the center region of a tree trunk.

Heat-fuse To join by softening or melting the edges with heat and pressing them together.

Heat of hydration The thermal energy given off by concrete or gypsum as it cures.

Heating, ventilation, and air conditioning (HVAC) The system of components that maintain air temperature and humidity, and supply fresh air to the building interior.

Heat-treated glass Glass that is strengthened by a heat treatment process; either *heat-strengthened glass* or *tempered glass*.

Heat recovery ventilator A mechanical device that exhausts air from a building while recovering much of the sensible heat from the exhausted air and transferring it to the incoming air. Also called an air-to-air heat exchanger. *See also* **energy recovery ventilator**.

Heat-strengthened glass *Heat-treated glass* that is not as strong as tempered glass and that may not be used as *safety glazing*.

Heaving The forcing upward of ground or buildings by the action of frost or pile driving.

Heavy Timber construction A type of wood construction made from large wood members and solid timber decking in a post-and-beam configuration; in the International Building Code, buildings of Type IV-HT construction, consisting of heavy timber interior construction and noncombustible exterior walls, which are considered to have moderate fire-resistive properties.

High-density overlay (HDO) A resin-treated overlay applied to plywood panels to achieve a smoother, more durable face.

High-lift grouting A method of constructing a reinforced masonry wall in which the *reinforcing bars* are embedded in grout in story-high increments.

High performance concrete (HPC) Concrete with an ultimate compressive strength of 8000 psi (55 MPa) or greater, but less than 17,000 psi (120 MPa).

High-range sealant A *sealant* that is capable of a high degree of elongation without rupture.

High-range water-reducing admixture *See* **superplasticizer**.

High-strength bolt A bolt designed to connect steel members by clamping them together with sufficient force that the load is transferred between them by friction.

Hip The diagonal intersection of planes in a hip roof.

Hip rafter A roof *rafter* at the intersection of two sloping roof planes. *See also* **common rafter**.

Hip roof A roof consisting of four sloping planes that intersect to form a pyramidal or elongated pyramid shape.

Hollow brick Clay brick with up to 60 percent void area.

Hollow concrete masonry Concrete masonry units that are manufactured with open cores, such as ordinary concrete blocks.

Hollow-core door A door consisting of two face veneers separated by an airspace, with solid wood spacers around the four edges. The face veneers are usually connected by a grid of thin spacers within the airspace.

Hollow-core slab A precast concrete slab element that has internal longitudinal cavities to reduce its self-weight.

Hollow structural section (HSS) Hollow steel cylindrical or rectangular shapes used as structural members. Also called *structural tubing*.

Hook A semicircular bend in the end of a *reinforcing bar*, made for the purpose of anchoring the end of the bar securely into the surrounding concrete.

Hopper window A window whose sash pivots on an axis along or near the sill and that opens by tilting toward the interior of the building.

Horizontal reinforcing Steel reinforcing that runs horizontally in a masonry wall in the form of either welded grids of small-diameter metal rods or larger conventional *reinforcing bars*.

Hose stream test A standard laboratory test to determine the relative ability of a building assembly to stand up to water from a fire hose after a specified period of fire testing.

Hot-dip galvanizing A method of *galvanizing* in which a steel member or assembly is dipped into a bath of molten zinc.

Hot-rolled steel Steel formed into its final shape by passing it between rollers while it is very hot and still in a plastic state.

Housewrap A synthetic sheet material with water-resistive and air-resistive properties used as a substitute for asphalt-saturated felt or building paper to provide a protective layer in an exterior wall assembly.

HPC *See* **high performance concrete**.

HSS *See* **hollow structural section**.

HVAC *See* **heating, ventilation, and air conditioning**.

Hydrated lime Quicklime mixed with water, either in the factory or on the job site; an ingredient in masonry mortars, portland cement plaster, and gypsum plasters, to which materials it imparts properties such as workability, bulk, and smoothness; chemically, calcium hydroxide. Also called *slaked lime*.

Hydration The process by which cements combine chemically with water to harden.

Hydraulic cements Cementitious materials, such as portland cement and blast furnace slag, that harden by reacting with water and whose hardened products are not water soluble. Nonhydraulic cements, such as lime, can also be mixed with pozzolans to create cements with hydraulic properties.

Hydronic heating system A system that circulates warm water through convectors to heat a building.

Hydrostatic pressure Pressure exerted by standing water.

Hygroscopic Readily absorbing and retaining moisture.

Hyperbolic paraboloid shell A concrete roof structure with a saddle shape.

I

IBC *See* **International Building Code and International Residential Code**.

I-beam Obsolete term; an American Standard section of hot-rolled steel, an archaic structural steel shape. (This term should not be applied to modern wide-flange steel sections.)

Ice and water shield *See* **rubberized underlayment**.

Ice barrier A sheet material, usually *rubberized underlayment* or sheet metal, applied to the lower portions of sloped roofs in cold climates to protect against *ice dams*.

Ice dam An obstruction along the eave of a roof, caused by the refreezing of water emanating from melting snow on the roof surface above.

ICF *See* **insulating concrete form**.

Igneous rock Rock formed by the solidification of magma.

IIC *See* **Impact Isolation Class**.

I-joist A manufactured wood framing member whose cross-sectional shape resembles the letter *I*.

Impact Isolation Class (IIC) An index of the resistance of a floor-ceiling assembly to the transmission of *structure-borne sound* from a room above to the room below, based on measurements taken according to ASTM E492.

Impact wrench A device for tightening bolts and nuts by means of rapidly repeated torque impulses produced by electrical or pneumatic energy.

Incising Short, repetitive cuts made in the surface of a wood member to increase its absorption of treatment chemicals.

Ingot A large block of cast metal.

Insulating concrete form (ICF) A system of lightweight components, most commonly made of rigid polystyrene insulating foam, used as *permanent formwork* for the casting of concrete walls.

Insulating glass A glazing unit made up of two or more sheets of glass with an airspace in between.

Insulating glass unit (IGU) *See* **insulating glass**.

Insulation *See* **acoustic insulation**, **thermal insulation**.

Intensive green roof A *green roof* with relatively deep soil capable of supporting a broad variety of plants and shrubs.

Interlayer In *laminated glass*, a thin, transparent plastic film sandwiched between the sheets of glass.

Internal drainage Providing a curtain wall with hidden channels and weep holes to remove any water that may penetrate the exterior layers of the wall.

Internal flashing In masonry, a flashing concealed with the masonry. Also called a *concealed* or *through-wall flashing*.

Internal gutter A *gutter* built into a roof assembly.

International Building Code (IBC) and International Residential Code (IRC) The predominant U.S. *model building codes*.

Interstitial ceiling A suspended ceiling with sufficient structural strength to support workers safely as they install and maintain mechanical and electrical installations above the ceiling.

Intrados The concave surface of an arch.

Intumescent coating A paint or mastic that expands to form a stable, insulating char when exposed to fire.

Inverted roof A membrane roof assembly in which the thermal insulation lies above the membrane.

IRC *See* **International Building Code and International Residential Code**.

Iron In pure form, a metallic element. In common usage, ferrous alloys other than steels, including cast iron and wrought iron.

Iron dog A heavy U-shaped staple used to tie the ends of heavy timbers together.

Ironworker A skilled laborer who erects steel building frames or places reinforcing bars in concrete construction.

Isocyanurate foam *See* **polyisocyanurate foam**.

Isolation joint A type of joint used to separate abutting materials or assemblies that should remain structurally independent, such as where new construction meets old, or where a nonstructural slab on grade abuts structural columns or walls.

J

Jack A device for exerting a large force over a short distance, usually by means of screw action or hydraulic pressure.

Jack rafter A shortened *rafter* that joins a hip or valley rafter.

Jack stud A shortened stud that carries a header above a wall opening. Also called a *trimmer stud*.

Jamb The vertical side of a door or window.

Jet burner A torch that burns fuel oil and compressed air, used in quarrying granite.

Joist One of a parallel array of light, closely spaced beams used to support a floor deck (*floor joist*) or low-slope roof (*ceiling joist*).

Joist band A broad, shallow concrete beam that supports one-way concrete joists whose depths are identical to its own.

Joist girder A light steel truss used to support open-web steel joists.

Joist hanger A sheet metal device used to create a structural connection where a joist is framed into a *header* or a *ledger*.

K

Keenes cement A proprietary, dense, crack-resistant gypsum plaster formulation.

Key A slot formed into a concrete surface for the purpose of interlocking with a subsequent pour of concrete; a slot at the edge of a precast member into which grout will be poured to lock it to an adjacent member; a mechanical interlocking of plaster with lath.

Kiln A furnace for firing clay or glass products; a heated chamber for seasoning wood; a furnace for manufacturing quicklime, gypsum hemihydrate, or portland cement.

King stud A full-length stud nailed alongside a *jack stud*.

Knee wall A short wall under the slope of a roof.

Knot A growth characteristic in wood, occurring where a branch joined the trunk of the tree from which the wood was sawed.

kPa Kilopascal; a metric unit of pressure equal to 1 kilonewton per square meter.

L

Labyrinth A cladding joint design in which a series of interlocking baffles prevents drops of water from penetrating the joint by momentum.

Lacquer A coating that dries extremely quickly through evaporation of a volatile solvent.

Lagging Planks placed between soldier beams to retain earth around an excavation.

Lag screw A large-diameter wood screw with a square or hexagonal head.

Laminate As a verb, to bond together in layers; as a noun, a material produced by bonding together layers of material.

Laminated glass A glazing material consisting of outer layers of glass laminated to an inner layer of transparent plastic.

Laminated strand lumber (LSL) Wood members made up of long shreds of wood fiber joined with a binder.

Laminated veneer lumber (LVL) Structural composite lumber made up of thin wood veneers joined with glue.

Laminated wood *See* **glue-laminated wood**.

Landing A platform in or at either end of a stair.

Lap joint A connection in which one piece of material is placed partially over another piece before the two are fastened together.

Lateral force A force acting generally in a horizontal direction, such as wind,

earthquake, or soil pressure acting against a foundation wall.

Lateral force resisting system The parts of a building structure that help to resist the lateral forces of wind and earthquake. *See* **braced frame**, **moment-resisting frame**, and **shear wall**.

Lateral thrust The horizontal component of the force produced by an arch, dome, vault, or rigid frame.

Latewood *See* **summerwood**.

Latex/polymer modified portland cement mortar A tile-setting mortar similar to *dry-set mortar*, but with additives that improve the cured mortar's freeze-thaw resistance, flexibility, and adhesion; used for *thin-set tile* applications.

Lath (Rhymes with "math.") A base material to which plaster is applied.

Lathe (Rhymes with "bathe.") A machine in which a piece of material is rotated against a sharp cutting tool to produce a shape, all of whose cross sections are circles; a machine in which a log is rotated against a long knife to peel a continuous sheet of veneer.

Lather (Rhymes with "rather.") One who applies lath.

Lay-in panel A finish ceiling panel that is installed merely by lowering it onto the top of the metal grid components of the ceiling.

Lead (Rhymes with "bed.") A soft, dull gray, easily formed *nonferrous metal*.

Lead (Rhymes with "bead.") In masonry work, a corner or wall end accurately constructed with the aid of a spirit level to serve as a guide for placing the bricks in the remainder of the wall.

Leader (Rhymes with "feeder.") *See* **downspout**.

Leaf The moving portion of a door.

Lean construction Methods of construction and its management that emphasize efficiency, elimination of waste, and continuous improvement in quality.

Ledger A horizontal wood member fastened to a wall or beam to which the ends of joists may be connected.

Lehr A chamber in which glass is annealed.

Let-in bracing Diagonal bracing that is nailed into notches cut in the face of the studs so as not to increase the thickness of the wall.

Level cut A saw cut that produces a level surface in a sloping rafter when the rafter is in its final position. *See also* **plumb cut**.

Leveling plate A steel plate placed in grout on top of a concrete foundation to create a level bearing surface for the lower end of a steel column.

Lewis A device for lifting a block of stone by means of friction exerted against the sides of a hole drilled in the top of the block.

Life-cycle analysis (LCA) A comprehensive method of describing the environmental impacts of a material or product, accounting for all phases of its life from resource extraction through final disposal or reuse. Also called *cradle-to-grave analysis*.

Life-cycle-cost A cost that takes into account both the first cost and the costs of maintenance, replacement, fuel consumed, monetary inflation, and interest over the life of the object being evaluated.

Light A sheet of glass. Also spelled *lite*.

Light gauge steel stud A length of thin sheet metal formed into a stiff shape and used as a wall framing member.

Light to solar gain (LSG) ratio The visible light transmittance of a glazing unit divided by the solar heat gain coefficient, a measure of the energy-conserving potential of the unit.

Lightweight aggregate Low-density aggregate used to make lightweight concrete, mortar, and plaster; in concrete, aggregate with a density of less than 70 lb/ft^3 (1120 kg/m^3).

Lignin The natural cementing substance that binds together the cellulose in wood.

Lime A nonhydraulic cementitious material, used as an ingredient in mortars and plasters. *See also* **hydrated lime, quicklime**.

Lime mortar Masonry mortar made from a mix of lime, sand, and water; used principally in the restoration of historic structures.

Lime putty *See* **Finish lime**.

Limestone A sedimentary rock consisting of calcium carbonate, magnesium carbonate, or both.

Linear metal ceiling A finish ceiling whose exposed face is made up of long, parallel elements of sheet metal.

Liner A piece of marble doweled and cemented to the back of another sheet of marble.

Line wire Wire stretched across wall studs as a base for the application of metal mesh and stucco.

Linoleum A resilient floor covering material composed primarily of ground cork and linseed oil on a burlap or canvas backing.

Lintel A beam that carries the load of a wall across a window or door opening.

Liquid limit The moisture content at which a soil arrives at a flowable consistency; a relative indication of soil cohesiveness.

Liquid sealant Gunnable *sealant*.

Lite A sheet of glass. Also spelled *light*.

Live load Nonpermanent loads on a building caused by the weights of people, furnishings, machines, vehicles, and goods in or on the building.

Load A weight or force acting on a structure.

Loadbearing Supporting a superimposed weight or force.

Loadbearing wall *See* **bearing wall**.

Load indicator washer A disk placed under the head or nut of a high-strength bolt to indicate sufficient tensioning of the bolt by means of the deformation of ridges on the surface of the disk. Also called a *direct tension indicator washer*.

Locally sourced material *See* **regional material**.

Lockpin and collar fastener A boltlike device that is passed through holes in structural steel components, held in very high tension, and closed with a steel ring that is squeezed onto its protruding shank.

Lockstrip gasket A synthetic rubber strip compressed around the edge of a piece of glass or a wall panel by inserting a spline (lockstrip) into a groove in the strip.

Longitudinal shrinkage In wood, shrinkage along the length of the log.

Lookout A short *rafter*, running perpendicular to the other rafters in the roof, that supports a rake overhang.

Louver A construction of numerous sloping, closely spaced slats used to diffuse air or to prevent the entry of rainwater into a ventilating opening.

Low-e coating *See* **low-emissivity coating**.

Low-emissivity coating A surface coating for glass that selectively reflects solar radiation of different wavelengths so as to allow high visible light transmittance while reflecting some or all types of infrared (heat) radiation. Also called *low-e coating*.

Low-lift grouting A method of constructing a reinforced masonry wall in which the *reinforcing bars* are embedded in grout in increments not higher than 4 feet (1200 mm).

Low-range sealant A *sealant* that is capable of a relatively slight degree of elongation prior to rupture; a *caulk*.

Low-slope roof A roof with a slope less than 3:12 to 2:12 (1 in 4 to 1 in 6). A roof pitched so near to horizontal that it must be made waterproof with a continuous membrane rather than shingles; commonly and inaccurately referred to as a "flat roof."

LSG *See* **light to solar gain ratio**.

LSL *See* **laminated strand lumber**.

Luffing-boom crane A heavy-duty lifting device that uses a tower-mounted boom that can rotate in any vertical plane as well as in a horizontal plane.

Lumber Sawed, solid wood members for use in construction.

LVL *See* **laminated veneer lumber**.

M

Machine grading The grading of wood for its structural properties, performed by automated machinery, as distinct from *visual grading*.

Macrofiber reinforcing In concrete, fibrous reinforcement capable of providing resistance to drying shrinkage and thermal stresses, and in some specialized concretes, also capable of acting as primary reinforcing. *See also* **microfiber reinforcing**.

Mandrel A stiff steel core placed inside the thin steel shell of a sitecast concrete pile to prevent it from collapsing during driving.

Mansard A roof shape consisting of two superimposed levels of hip roofs with the lower level at a steeper pitch than the upper.

Manufactured home A transportable house that is entirely factory-built on a steel underframe supported by wheels; referred to in the past as a *mobile home*.

Marble A metamorphic rock formed from limestone by heat and pressure.

Mason One who builds with bricks, stones, or concrete masonry units; one who works with concrete.

Masonry Brickwork, concrete blockwork, and stonework.

Masonry cement A hydraulic cement made from a blend of portland cement, lime, and other dry admixtures designed to increase the workability of the mortar. *See also* **cement–lime mortar, mortar cement**.

Masonry opening The clear dimension required in a masonry wall for the installation of a specific window or door unit.

Masonry unit A *brick*, stone, *concrete block*, *glass block*, or hollow clay tile intended to be laid in mortar.

Masonry veneer A single wythe of masonry used as a facing over a frame of wood or metal.

Mass timber Systems of building construction relying on large, prefabricated wood components, such as *cross-laminated timber* and *glue-laminated wood*.

Mass wall An exterior wall, usually masonry or concrete, that relies primarily on its thickness and density to resist the passage of water.

MasterFormat The trademarked name of a uniform indexing system for construction specifications, created by the Construction Specifications Institute and Construction Specifications Canada.

Mastic A viscous, doughlike, adhesive substance; can be any of a large number of formulations for different purposes, such as sealants, adhesives, glazing compounds, or roofing cements.

Mat foundation A single concrete footing that is essentially equal in area to the area of ground covered by the building.

Maximum allowable slope The steepest angle at which an excavation may be sloped so that the soil will not slide back into the hole. Also called the *angle of repose*.

Means of egress The parts of a building, such as exit stairways, corridors, and exit access pathways, that provide safe routes out of a building in the case of fire or other emergency.

Medium-density fiberboard (MDF) A fine-grained wood fiber and resin panel product.

Medium-density overlay (MDO) A medium-weight, resin-treated overlay applied to plywood panels to achieve a smoother, more durable face.

Medium-range sealant A *sealant* material that is capable of a moderate degree of elongation before rupture.

Meeting rail The wood or metal bar along which one sash of a double-hung, single-hung, or sliding window seals against the other.

Member An element of a structure, such as a beam, girder, column, joist, piece of decking, stud, or component of a truss.

Membrane A sheet material that may be used to control the passage of liquid water, water vapor, and/or air.

Membrane fire protection A ceiling used to provide fire protection to the structural members above.

Metal decking Corrugated metal sheets used as the structural base for floors ("floor decking") and roofs ("roof decking") in steel frame construction. *See also* **cellular decking** and **composite metal decking**.

Metal lath A steel mesh used primarily as a base for the application of plaster.

Metallic-coated steel Steel sheet coated with zinc or zinc-aluminum for improved corrosion resistance.

Metamorphic rock A rock created by the action of heat or pressure on a sedimentary rock or soil.

Microfiber reinforcing In concrete, fibrous reinforcement against plastic shrinkage cracking. *See also* **macrofiber reinforcing**.

Microsilica *See* **silica fume**.

Middle strip The half-span-wide zone of a two-way concrete slab that lies midway between columns.

Mild steel Ordinary structural steel, containing less than three-tenths of 1 percent carbon.

Mill construction The traditional name for a construction type consisting of exterior masonry bearing walls and an interior framework of heavy timbers and solid timber decking. Also called *slow-burn construction*. *See also* **Heavy Timber construction**.

Milling Shaping or planing by using a rotating cutting tool.

Millwork Wood interior finish components of a building, including moldings, windows, doors, cabinets, stairs, mantels, and the like.

Minimum critical radiant flux exposure A measure of a material's resistance to ignition by the radiant heat of fire and hot gasses in adjacent spaces, usually applied to flooring materials.

Miter A diagonal cut at the end of a piece; the joint produced by joining two diagonally cut pieces at right angles.

Mobile home *See* **manufactured home**.

Model building code A code that is offered by a recognized national organization

as worthy of adoption by state or local governments.

Modified bitumen A natural *bitumen* with admixtures of synthetic compounds to enhance such properties as flexibility, plasticity, and durability.

Modified bitumen roof membrane A multi-ply *bituminous roof membrane* made from plies of factory-manufactured *modified bitumen* sheets.

Modular Conforming to a multiple of a fixed dimension.

Modular green roof A *green roof* system in which all components are provided in self-contained, easily transported and installed trays or modules.

Modular home A house assembled on the site from boxlike factory-built sections.

Modulus of elasticity An index of the stiffness of a material, derived by measuring the elastic deformation of the material as it is placed under stress and then dividing the stress by the deformation.

Moisture barrier *See* **water-resistive barrier**.

Molding A strip of wood, plastic, or plaster with an ornamental profile.

Molding plaster A fast-setting gypsum plaster used for the manufacture of cast ornament.

Moment A force acting at a distance from a point in a structure so as to cause a tendency of the structure to rotate about that point. *See also* **bending moment, moment connection**.

Moment connection A connection between two structural members that is resistant to rotation between the members and therefore capable of transmitting *bending moments* between the connected members, as differentiated from a *shear connection*, which allows (slight) rotation. *See also* **fully restrained moment connection, partially restrained moment connection**, and **simple connection**.

Moment-resisting frame A structural building frame that is strengthened to resist lateral forces with *moment connections* between beams and columns.

Momentum The tendency of a moving body to continue to move in the same direction unless acted on by an outside force.

Monolithic Of a single massive piece.

Monolithic terrazzo A thin terrazzo topping applied to a concrete slab without an underbed.

Mortar A substance used to join masonry units, consisting of cementitious materials, fine aggregate, and water. *See also* **cement–lime mortar, lime mortar**. **Mortar admixture** *See* **admixture**.

Mortar bed tile *See* **thickset tile**.

Mortar cement In masonry, a blend of portland cement, lime, and other additives that produces mortar comparable in its bond strength properties to cement–lime mortar. *See also* **cement–lime mortar, masonry cement**.

Mortar deflection material A material placed in the airspace of a masonry cavity wall to catch mortar droppings and prevent clogging of weep holes at the bottom of the cavity. Also called *cavity drainage material.*

Mortise and tenon A joint in which a tonguelike protrusion (tenon) on the end of one piece is tightly fitted into a rectangular slot (mortise) in the side of the other piece.

Movement joint A line or plane along which movement is allowed to take place in a building or a surface of a building in response to such forces as moisture expansion and contraction, thermal expansion and contraction, foundation settling, and seismic forces.

MPa Megapascal; a unit of pressure equal to 1 meganewton per square meter.

Mud set tile *See* **thickset tile**.

Mud slab A slab of weak concrete placed directly on the ground to provide a (usually temporary) working surface that is hard, level, and dry.

Mullion A vertical or horizontal bar between adjacent window or door units; a framing member in a metal-and-glass curtain wall.

Muntin A small vertical or horizontal bar between small lites of glass in a sash.

Muriatic acid Hydrochloric acid.

Mushroom capital A flaring conical head on a concrete column.

N

Nail A sharp-pointed metal pin used for fastening wood.

Nail-base sheathing A sheathing material, such as wood boards or plywood, to which siding can be attached by nailing, as differentiated from one such as gypsum board or plastic foam board that is too soft to hold nails.

Nail-laminated timber (NLT) *Mass timber* panels fabricated from solid lumber aligned side-by-side and fastened with nails or screws; used as structural floor, wall, and roof elements.

Nail popping The loosening of nails holding gypsum board to a wall, caused by drying shrinkage of the studs.

Nail set A hardened steel punch used to drive the head of a nail to a level flush with or below the surface of the wood.

National Building Code of Canada (NBCC) The predominant Canadian *model building code.*

NBCC *See* **National Building Code of Canada**.

Near-infrared (NIR) radiation An invisible portion of the solar spectrum that accounts for more than half of the total heat energy in solar radiation.

Needle beam A steel or wood beam threaded through a hole in a bearing wall and used to support the wall and its superimposed loads during underpinning of its foundation.

Needling The use of *needle beams.*

Negative-side waterproofing Waterproofing applied to the inner side of a wall, acting to resist water passage from the opposite side.

Neoprene Polychloroprene, a synthetic rubber, sometimes used as an accessory material in waterproofing systems.

NIR radiation *See* **near-infrared radiation**.

NLT *See* **nail-laminated timber**.

Noise Reduction Coefficient (NRC) A legacy index of the proportion of incident sound that is absorbed by a surface, which is expressed as a decimal fraction of 1. *See also* **Sound Absorption Average**.

Nominal dimension An approximate dimension assigned to a piece of material as a convenience in describing its size, as distinct from its *actual dimension.*

Nonaxial In a direction not parallel to the long axis of a structural member.

Nonbearing Not carrying a structural load.

Nonferrous metal Any metal other than iron or an iron alloy. Aluminum, copper, lead, and zinc are examples of nonferrous metals frequently used in building construction.

Nonhydraulic cements *Cementitious materials*, such as gypsum and lime, that remain water soluble after curing. *See also* **hydraulic cements**.

Nonmovement joint A connection between materials or elements that is not designed to allow movement between the parts.

Nonworking joint *See* **nonmovement joint**.

Nosing The projecting forward edge of a stair tread.

NRC *See* **Noise Reduction Coefficient**.

Nut A fastener, usually metallic, with internal helical threads, used to close a *bolt*.

O

o.c. Abbreviation for "on center," meaning that the spacing of framing members is measured from the center of one member to the center of the next, rather than the clear spacing between members.

Occupancy In the International Building Code, a definition of the types of activities that occur within the building or a part of the building relating to considerations of life safety.

Ogee An S-shaped curve.

OITC *See* **Outdoor-Indoor Transmission Class.**

OmniClass Construction Classification System The trademarked name for a system of describing building information encompassing a broad range of possible organizing criteria.

One-way action The structural action of a slab that spans between two parallel beams or bearing walls.

One-way concrete joist system A reinforced concrete framing system in which closely spaced concrete joists span between parallel beams or bearing walls.

One-way solid slab A reinforced concrete floor or roof slab that spans between parallel beams or bearing walls.

Open-truss wire stud An archaic wall framing member in the form of a small steel truss, no longer used in contemporary construction.

Open-web steel joist A lightweight, prefabricated, welded steel truss used at closely spaced intervals to support floor or roof decking.

Optical-quality ceramic A transparent, glasslike material that is used as a fire-rated glazing sheet.

Optimum value engineering *See* **advanced framing techniques**.

Ordinary construction A traditional building type with exterior masonry bearing walls and an interior structure of balloon framing.

Organic soil Soil containing decayed vegetable and/or animal matter; topsoil.

Oriented strand board (OSB) A building panel composed of long shreds of wood fiber oriented in specific directions and bonded together under pressure.

Oriented strand lumber (OSL) *Structural composite lumber* made from shredded wood strands, coated with adhesive, and pressed into a rectangular cross section.

OSB *See* **oriented strand board**.

OSL *See* **oriented strand lumber**.

Outdoor-Indoor Transmission Class (OITC) A *Sound Transmission Class* rating weighted for low-frequency sounds associated with outdoor noise such as traffic and street noise, airport activity, etc. Used to rate the acoustic isolation performance of exterior windows, doors, walls, and other building enclosure components.

Oxidation Corrosion; rusting; rust; chemically, the combining with oxygen.

P

Paint A heavily pigmented coating applied to a surface for decorative and/or protective purposes.

Pan A form used to produce the cavity between joists in a one-way concrete joist system.

Panel A broad, thin piece of wood; a sheet of building material such as plywood or particleboard; a prefabricated building component that is broad and thin, such as a curtain wall panel; a rectangular area within a truss bounded by two vertical interior members.

Panel door A wood door in which one or more thin panels are held by stiles and rails.

Panelized construction A method of prefabricated wood light frame construction, in which whole sections of walls or floors are framed and sheathed in the factory and then transported to the construction site for erection.

Panic hardware A mechanical device that opens a door automatically if pressure is exerted against the device from the interior of the building.

Parallel strand lumber (PSL) *Structural composite lumber* made of wood shreds oriented parallel to the long axis of each piece and bonded together with adhesive.

Parapet The region of an exterior wall that projects above the level of the roof.

Parging Portland cement plaster applied over masonry to make the masonry less permeable to water.

Partially restrained moment connection A steel frame *moment connection* that is less rigid than a *fully restrained moment connection* but that still possesses a usable degree of resistance to rotation.

Particleboard A building panel composed of small particles of wood bonded together under pressure.

Parting compound *See* **form release compound**.

Partition An interior nonload-bearing wall.

Patterned glass Glass into which a texture has been rolled during manufacture.

Pattern rafter A wood *rafter* cut to size and shape and then used to trace cuts onto additional wood members so as to assure consistent dimensions among all rafters.

Paver A half-thickness brick used as finish flooring.

Pediment The gable end of a roof in classical architecture.

Penetrometer A device for testing the resistance of a material to penetration, usually used to make a quick, approximate determination of its compressive strength.

Penny A designation of nail size, abbreviated as "d."

Performance-based building code A set of legal regulations that mandate performance outcomes rather than specific construction details and practices.

Performance category A system for specifying the nominal thickness of a structural wood panel. Actual panel thickness may deviate from the performance category within accepted tolerances.

Periodic kiln A kiln that is loaded and fired in discrete batches, as differentiated from a tunnel kiln, which is operated continuously.

Perlite Expanded volcanic glass, used as a *lightweight aggregate* in concrete and plaster and as an insulating fill.

Perm A unit of vapor permeance, a measure of a material's permeability to the diffusion of water vapor.

Permanent formwork Concrete formwork that remains permanently in place after concrete is poured and cured;

that is, it becomes part of the finished construction.

Pervious concrete Concrete with a high percentage of void space, used as a paving material that allows stormwater to pass through into the soil below.

PF *See* **phenol-formaldehyde**.

Phased construction *See* **fast track construction**.

Phenol-formaldehyde (PF) A structural wood adhesive and binder, suitable for exterior exposure and associated with relatively low *formaldehyde* gas emissions.

Photochromic glass Glass that changes its optical properties in response to light intensity.

Photovoltaic (PV) Capable of converting light into electricity.

Pier A caisson foundation unit.

Pilaster A vertical, integral stiffening rib in a masonry or concrete wall.

Pile A long, slender piece of material driven into the ground to act as an element of a foundation.

Pile cap A thick slab of reinforced concrete poured across the top of a pile cluster to cause the cluster to act as a unit in supporting a column or grade beam.

Piledriver A machine for driving piles.

Pill test A test of a flooring material's propensity for flame spread when exposed to a burning tablet intended to simulate a dropped lit cigarette, match, or similar hazard.

Pintle A metal device used to transmit compressive forces between superimposed columns in Mill construction.

Pitch The slope of a roof or other plane, often expressed as inches of rise per foot of run; a dark, viscous hydrocarbon distilled from coal tar; a viscous resin found in wood.

Pitched roof A sloping roof.

Pivoting window A window that opens by rotating around its vertical centerline.

Plainsawn lumber Lumber sawn in such a way that significant portions of the growth rings are oriented roughly flat relative to the board's broader face.

Plainsliced veneer Veneer sliced from a log without regard to the direction of the annual rings, as distinct from *quartersliced*.

Plain slicing Cutting a log into veneers without regard to the direction of the annual rings.

Plan An architectural drawing, representing the layout of walls and floor areas as seen from above ("floor plan") or ceilings as seen from below ("ceiling plan").

Planing Smoothing the surface of a piece of wood, stone, or steel with a cutting blade.

Plank flooring Solid wood finish flooring members 3 inches (75 mm) or more in width.

Plaster A cementitious material, usually based on gypsum or portland cement, applied to lath or masonry in paste form to harden into a finish surface.

Plasterboard *See* **gypsum board**.

Plaster of Paris *See* **calcined gypsum**.

Plaster screeds Intermittent spots or strips of plaster used to establish the level to which a large plaster surface will be finished.

Plastic A synthetically produced giant molecule, mostly based on carbon chemistry.

Plasticity The ability to retain a shape attained by pressure deformation.

Plastic laminate flooring A finish material for floors that consists of a thin decorative and wearing layer of melamine laminate glued to a wood composite substrate.

Plastic lumber Lumberlike products with a plastic content of 50 percent or more. *See also* **structural-grade plastic lumber**.

Plastic shrinkage cracking Cracking in freshly mixed concrete, most commonly in slabs, that occurs when the surface of the concrete dries too rapidly.

Plate A broad sheet of rolled metal ¼ inch (6.35 mm) or more thick; a two-way concrete slab; a horizontal top or bottom member in a platform frame wall structure.

Plate girder A large beam made up of steel plates, sometimes in combination with steel angles, that are welded, bolted, or riveted together.

Plate glass Glass of high optical quality, produced by grinding and polishing both faces of a glass sheet.

Platform frame A wooden building frame composed of closely spaced members nominally 2 inches (51 mm) thick in which the wall members do not run past the floor framing members.

Plenum The space between the ceiling of a room and the structural floor above, used as a passage for ductwork, piping, and wiring.

Plumb Vertical.

Plumb cut A saw cut that produces a vertical (plumb) surface in a sloping rafter after the rafter is in its final position. *See also* **level cut**.

Plumbing up The process of making a steel building frame vertical and square.

Ply A layer, such as a layer of felt in a built-up roof membrane or a layer of veneer in plywood.

Plywood A wood panel composed of an odd number of layers of wood veneer bonded together under pressure.

PMR *See* **protected membrane roof**.

Pneumatically placed concrete *See* **shotcrete**.

Pointing The process of applying mortar to the surface of a mortar joint after the masonry has been laid, either as a means of finishing the joint or to repair a defective joint. *Raked mortar joints* can also be pointed with elastomeric sealant.

Pointing mortar Mortar used for the pointing of masonry joints, generally of relatively low strength and with good workability and adhesion characteristics.

Poke-through fitting An electrical outlet that is installed by drilling a hole through a floor, inserting the outlet from above, and bringing in the wiring from the plenum below.

Polycarbonate An extremely tough, strong, usually transparent plastic used for window and skylight glazing, light fixture globes, doorsills, and other applications.

Polyethylene A thermoplastic widely used in sheet form for vapor retarders and temporary construction coverings.

Polyisocyanurate foam A thermosetting plastic foam with thermal insulating properties.

Polymer A large molecule composed of many identical chemical units.

Polypropylene A plastic formed by the polymerization of propylene.

Polystyrene foam A thermoplastic foam with thermal insulating properties.

Polysulfide A high-range gunnable *sealant*.

Polyurethane Any of a large group of resins and synthetic rubber compounds used in sealants, varnishes, insulating foams, and roof membranes.

Polyurethane foam A thermosetting foam with thermal insulating properties.

Polyvinyl butyral (PVB) A transparent plastic used as an *interlayer* in the fabrication of *laminated glass*.

Polyvinyl chloride (PVC) A thermoplastic material widely used in construction products, including plumbing pipes, floor tiles, wall coverings, and roof membranes. Called "vinyl" for short.

Ponding The accumulation of standing water on a low-slope roof due to inadequate drainage.

Poorly graded soil Soil with less than a full range of particle sizes.

Poorly sorted soil *See* **well graded soil**.

Portal frame A rigid frame; two columns and a beam attached to one another with moment connections.

Portland cement A gray or white powder composed principally of calcium silicates, which, when combined with water, hydrates to form the binder in concrete, mortar, and stucco.

Portland cement plaster Plaster made from a mixture of portland cement, lime, sand, and water; commonly used as an exterior finish material. Also called *stucco*.

Postconsumer recycled material *Recycled materials content* that originates as waste generated by the final user of the material, as opposed to *preconsumer recycled material*.

Posttensioning Compressing the concrete in a structural member by tensioning high-strength steel tendons against it after the concrete has cured.

Pour To cast concrete; an increment of concrete casting carried out without interruption.

Powder coating A finish coating produced by applying a powder consisting of thermosetting resins and pigments, which is adhered to the substrate by electrostatic attraction and fused into a continuous film in an oven.

Powder-driven Inserted by a gunlike tool using energy provided by an exploding charge of gunpowder.

Pozzolan A *supplementary cementitious material*, such as fly ash, silica fume, and some naturally occurring shales and clays, that has few or no inherent cementitious properties but that, in the presence of moisture, can react with calcium hydroxide released by other cementitious materials to create a hydraulic cement product. The Romans mixed natural pozzolans with lime to make the first hydraulic cement.

Precast concrete Concrete cast and cured in a location other than its final position in the structure.

Preconsumer recycled material *Recycled materials content* originating from manufacturing process waste, as opposed to *postconsumer recycled material*.

Predecorated gypsum board Gypsum board finished at the factory with a decorative layer of paint, paper, or plastic.

Prefabrication Construction that takes place in a factory or shop, rather than on the building site.

Preformed cellular tape sealant A *sealant* inserted into a joint in the form of a compressed sponge impregnated with compounds that cure to form a watertight seal.

Preformed joint filler A strip of rubbery or spongelike material designed to fit snugly into a gap between two materials.

Preformed solid tape sealant A *sealant* inserted into a joint in the form of a flexible strip of solid material.

Prehung door A door that is hinged to its frame (in which other hardware has often been installed) in the factory or shop prior to delivery to the construction site. *See also* **slab door**.

Prescriptive building code A set of legal regulations that mandate specific construction details and practices rather than establish performance standards.

Preservative-treated wood Wood that has been impregnated with preservative chemicals to increase its resistance to decay and biological attack. Also commonly called *pressure-treated wood*.

Pressure equalization chamber (PEC) The air space behind a joint or opening in a cladding system bounded by an air barrier that acts to balance external air pressures.

Pressure-equalized design The design of a cladding or joint system that relies on the neutralization of wind pressures to control water entry.

Pressure-treated wood Wood that has been impregnated with chemicals under pressure for the purpose of retarding decay or reducing combustibility.

Prestressed concrete Concrete that has been pretensioned or posttensioned.

Prestressing Applying an initial compressive stress to a concrete structural member, either by *pretensioning* or *posttensioning*.

Pretensioning Compressing the concrete in a structural member by pouring the concrete for the member around stretched high-strength steel strands, curing the concrete, and releasing the external tensioning force on the strands.

Priming Covering a surface with a coating that prepares it to accept another coating or a sealant.

Protected membrane roof (PMR) A membrane roof assembly in which the thermal insulation lies above the membrane.

Protection board Semirigid board or sheet material placed over a waterproofing or roofing layer, to protect the layer from damage.

PSL *See* **parallel strand lumber**.

Pultrusion The process of producing a shaped linear element by pulling glass fibers through a bath of uncured plastic, then through a heated, shaped die in which the plastic hardens.

Punty A metal rod used in working with hot glass.

Purlin A beam that spans across the slope of a steep roof to support the roof decking.

Putty A simple glazing compound used to seal around a small light.

PV *See* **photovoltaic**.

PVB *See* **polyvinyl butyral**.

PVC *See* **polyvinyl chloride**.

Pyrolitic coating A coating applied at a very high temperature.

Q

Quarry An excavation from which building stone is obtained; the act of taking stone from the ground.

Quarry bed A plane in a building stone that was horizontal before the stone was cut from the quarry. Also called *grain*.

Quarry sap Excess water found in rock at the time of its quarrying.

Quarry tile A large clay floor tile, usually unglazed.

Quartersawn lumber For softwoods, lumber sawn in such a way that growth rings are aligned at an angle of approximately 45 degrees or steeper relative to the board's broader face. For hardwoods, sawn such that the growth rings are aligned at an angle of approximately 60 degrees or steeper to the broader face.

Quartersliced veneer Veneer sliced in such a way that the annual rings appear

closely spaced and run roughly perpendicular to the face of each veneer.

Quenching The rapid cooling of metal so as to alter its physical properties; a form of heat treatment.

Quicklime Produced by burning calcium carbonate found in limestone or seashells; once hydrated, used as an ingredient in mortars and plasters; chemically, calcium oxide. *See also* **hydrated lime**.

Quoin (pronounced "coin") A corner reinforcing of cut stone or bricks in a masonry wall, usually done for decorative effect.

R

Rabbet A longitudinal groove cut at the edge of a member to receive another member. Also called a *rebate*.

Radial shrinkage In wood, shrinkage perpendicular to the growth rings.

Radiant barrier A reflective foil or metal placed adjacent to an airspace in roof or wall assemblies as a deterrent to the passage of infrared energy.

Radiant heating system Providing heat to spaces and their inhabitants by heating one or more surfaces of each room. The heated surface is usually either the floor or the ceiling. Heat is usually provided either by electric resistance coils or by hot-water tubing.

Radiator *See* **convector**.

Raft A mat footing.

Rafter A framing member that runs up and down the slope of a steep roof.

Rail A horizontal framing piece in a panel door; a handrail.

Rainscreen cladding *See* **drained cladding**.

Raised access flooring *See* **access flooring**.

Rake The sloping edge of a steep roof.

Raked mortar joint A mortar joint in which mortar has been removed from the portion of the joint closest to the surface of the masonry.

Raker A sloping brace for supporting sheeting around an excavation.

Ram A hydraulic piston device used for bending steel, tensioning steel strands in prestressed concrete, or lifting heavy loads.

Rapidly renewable material A *bio-based material* that can be cultivated and harvested in a relatively short time span.

Random stone masonry *See* **uncoursed stone masonry**.

Ratchet A mechanical device with sloping teeth that allows one piece to be advanced against another in small increments but not to move in the reverse direction.

Ray A tubular cell that runs radially in a tree trunk.

RBM *See* **reinforced brick masonry**.

Rebar *See* **reinforcing bar**.

Rebate *See* **rabbet**.

Recycled materials content The percentage of a material's composition, usually based on weight, derived from waste materials that would otherwise enter the waste stream. May consist of *postconsumer recycled material* and/or *preconsumer recycled material*.

Reflective coated glass Glass onto which a thin layer of metal or metal oxide has been deposited to reflect light and/or heat.

Regional material A construction material extracted and produced close to the construction site.

Reglet A slot, usually horizontal, and inclined in cross section, into which a flashing or roof membrane may be inserted in a concrete or masonry surface.

Reinforced brick masonry (RBM) Brickwork into which steel bars have been embedded to impart tensile strength to the construction.

Reinforced concrete Concrete work into which steel bars have been embedded to impart tensile strength to the construction.

Reinforcing bar A member, usually made of steel, added to concrete or masonry to impart tensile strength and *ductility*. Also called *rebar*.

Relative humidity A percentage representing the ratio of the amount of water vapor contained in a mass of air to the maximum amount of water it could contain under the existing conditions of temperature and pressure.

Relieved back A longitudinal groove or series of grooves cut from the back of a flat wood molding or flooring strip to minimize cupping forces and make the piece easier to fit to a flat surface.

Removable glazing panel A framed sheet of glass that can be attached to a window sash to increase its thermal insulating properties.

Replacement window A window unit that is designed to be installed easily in an opening left in a wall by a deteriorated window unit that has been removed.

Repointing The process of removing deteriorated mortar from the zone near the surface of a brick wall and inserting fresh mortar. *See also* **tuckpointing**.

Reshoring Inserting temporary supports under concrete beams and slabs after the formwork has been removed to prevent overloading before the concrete achieves its full strength.

Resilient clip A springy mounting device for plaster or gypsum board that helps reduce the transmission of sound vibrations through a wall or ceiling.

Resilient flooring A manufactured sheet or tile flooring made of asphalt, polyvinyl chloride, linoleum, rubber, or other elastic material.

Resin A natural or synthetic, solid or semisolid organic material of high molecular weight, used in the manufacture of paints, varnishes, and plastics.

Restraightening A step in the finishing of concrete slabs for the purpose of removing minor undulations produced during floating or troweling.

Retaining wall A wall that resists horizontal soil pressures at an abrupt change in ground elevation.

Retarding admixture An *admixture* used to slow the curing of concrete, mortar, or plaster.

Ridge beam A structural beam supporting the upper ends of rafters in a sloped roof required where the rafters are not tied at their lower ends.

Ridge board A nonstructural framing member against which the upper ends of rafters are fastened.

Ridge vent A screened, water-shielded ventilation opening that runs continuously along the ridge of a gable roof.

Riftsawn lumber For hardwoods, lumber sawn such that the growth rings are aligned at an angle of approximately 30 to 60 degrees to the broader face.

Riftsliced veneer Veneer sliced in a manner similar to *quartersliced veneer*, but such that the ray structure of the wood is visually minimized.

Rigid connection *See* **fully restrained moment connection**.

Rim joist *See* **band joist**.

Rise A difference in elevation, such as the rise of a stair from one floor to the next or the rise per foot of run in a sloping roof.

Riser A single vertical increment of a stair; the vertical face between two treads in a stair; a vertical run of plumbing, wiring, or ductwork.

Rivet In structural steel construction, an archaic fastener in which a second head is formed after the fastener is in place; a threadless fastener used in sheet metal work.

Rock anchor A posttensioned rod or cable inserted into a rock formation for the purpose of tying it together.

Rock wool An insulating material manufactured by forming fibers from molten rock.

Roofer One who installs roof coverings.

Roofing The material used to make a roof watertight, such as shingles, slate, tiles, sheet metal, or a roof membrane; the act of applying roofing.

Roof membrane A waterproof sheet or multi-ply assembly that protects a low-slope roof from water penetration.

Roof window Either an openable glazed unit installed in the sloping surface of a roof or, more specifically, a glazed roof unit with inward sash operation to allow easy cleaning.

Rotary-sliced veneer A thin sheet of wood produced by rotating a log against a long, sharp knife blade in a lathe.

Rough arch An arch made from masonry units that are rectangular rather than wedge-shaped.

Rough carpentry Framing carpentry, as distinguished from *finish carpentry*.

Roughing in The installation of mechanical, electrical, and plumbing components that will not be exposed to view in the finished building.

Rough opening The clear dimensions of the opening that must be provided in a wall frame to accept a given door or window unit.

Rowlock A brick laid on its long edge, with its end exposed in the face of the wall.

RSI-value A numerical measure of resistance to the flow of heat, expressed in metric units; the reciprocal of *U-Factor*.

Rubberized underlayment An adhered bituminous sheet material that self-heals around nails and is applied to roof sheathing to prevent the entry of water. Also called *ice and water shield*.

Rubble Unsquared stones.

Run Horizontal dimension in a stair or sloping roof.

Runner channel A steel member from which furring channels and lath are supported in a suspended plaster ceiling.

Running bond Brickwork consisting entirely of stretchers.

Runoff bar One of a pair of small rectangular steel bars attached temporarily at the end of a prepared groove for the purpose of permitting the groove to be filled to its very end with weld metal.

Run plaster ornament A linear molding produced by passing a profiled sheet metal or plastic template back and forth across a mass of wet plaster.

R-value A numerical measure of resistance to the flow of heat; usually expressed in inch-pound units, but also sometimes used with metric units; the reciprocal of *U-Factor*.

S

Safety glazing Glass or plastic glazing material that when broken does not create hazardous shards and that is permitted for use in locations in buildings at risk of occupant impact; most commonly tempered glass or laminated glass.

Safing *See* **fire safing**.

Sand cushion terrazzo Terrazzo with an underbed that is separated from the structural floor deck by a layer of sand.

Sand-mold brick, sand-struck brick A brick made in a mold that was wetted and then dusted with sand before the clay was placed in it.

Sandstone A sedimentary rock formed from sand; classified by ASTM C119 in the Quartz-Based Dimension Stone group.

Sandwich panel A panel consisting of two outer faces of wood, metal, gypsum, or concrete bonded to a core of insulating foam.

Sapwood The living wood in the outer region of a tree trunk or branch.

Sash A frame that holds glass.

Sawn veneer Thin sheets of wood produced by sawing rather than slicing with a knife blade.

SBS *See* **styrene-butadiene-styrene**.

Scab A piece of framing lumber nailed to the face of another piece of lumber.

Scarf joint A glued end connection between two pieces of wood using a sloping cut to create a large surface for the glue bond to allow it to develop the full tensile strength of the wood that it connects.

SCC *See* **self-consolidating concrete**.

SCOF *See* **static coefficient of friction**.

Scratch coat The first of two base-coat plaster applications in a three-coat plaster.

Screed A strip of wood, metal, or plaster that establishes the level to which concrete or plaster will be placed.

Screw port A three-quarter circular profile in an aluminum extrusion, made to accept a screw driven parallel to the long axis of the extrusion.

Screw slot A serrated slot profile in an aluminum extrusion, made to accept screws driven at right angles to the long axis of the extrusion.

Scupper An opening through a parapet through which water can drain over the edge of a flat roof.

Sealant A rubberlike, adhesive material, usually applied in liquid or tape form, used to seal a joint, gap, or crack against the passage of air and water.

Sealant gun A tool for injecting *sealant* into a joint.

Sealer A coating used to close the pores in a surface, usually in preparation for the application of a finish coating.

Seasoning The drying of wood to bring its moisture content into equilibrium with ambient conditions.

Seated connection A connection in which a steel beam rests on top of a steel angle or tee that is fastened to a column or girder.

Section An architectural drawing representing a vertically cut plane through a whole building, part of a building, or detail.

Security glass A glazing sheet with multiple laminations of glass and plastic designed to stop bullets.

Sedimentary rock Rock formed from materials deposited as sediments, such as sand or seashells, which form sandstone and limestone, respectively.

Segregation Separation of the constituents of wet concrete caused by excessive handling or vibration.

Seismic Relating to earthquakes.

Seismic load A force on a structure caused by movement of the earth relative to the structure during an earthquake.

Seismic separation joint A building separation joint that allows adjacent building masses to oscillate independently during an earthquake.

Self-adhered flashing A flexible, self-sticking flashing material, usually made of polymer-modified asphalt laminated to a plastic backing, with preapplied adhesive on one side.

Self-consolidating concrete (SCC) Concrete formulated so that it is highly flowable and fills formwork completely without needing *consolidation*.

Self-consolidating grout Grout formulated so that it is highly flowable.

Self-drilling Drills its own hole.

Self-furring metal lath Metal lath with dimples that space the lath away from the sheathing behind to allow plaster to penetrate the lath and key to it.

Self-tapping Creates its own screw threads on the inside of the hole.

Self-weight The weight of a beam or slab.

Semirigid connection *See* **partially restrained moment connection**.

Sequential construction A method of providing design and construction services in which each major phase of design and construction is completed before the next phase is begun.

Sequestered carbon *See* **carbon sequestration**.

Set To cure; to install; to recess the heads of nails; a punch for recessing the heads of nails.

Setting block A small block of synthetic rubber or lead used to support the weight of a sheet of glass at its lower edge.

Settlement joint A *building separation joint* that allows the foundations of adjacent building masses to settle at different rates.

SFRM *See* **spray-applied fire-resistive material**.

SGPL *See* **structural-grade plastic lumber**.

Shading coefficient The ratio of total solar heat passing through a given sheet of glass to that passing through a sheet of clear double-strength glass; mostly replaced in contemporary energy calculations by *solar heat gain coefficient*.

Shaft An unbroken vertical passage through a multistory building, used for elevators, wiring, plumbing, ductwork, and so on.

Shaft liner A thick gypsum panel used in metal-framed *shaft wall* systems.

Shaft wall A wall surrounding a *shaft*, usually with a specified degree of fire resistance.

Shake A shingle split from a block of wood.

Shake-on hardener A dry powder that is dusted onto the surface of a concrete slab before troweling to react with the concrete and produce a hard-wearing surface for industrial use.

Shale A rock formed from the consolidation of clay or silt.

Shallow foundation A building *foundation* located at the base of a wall or a column, bearing on soil relatively close to the ground surface.

Shear A deformation in which planes of material slide with respect to one another.

Shear connection A connection designed to resist only the tendency of one member to slide past the other, and not, as in a *moment connection*, to resist any tendency of the members to rotate with respect to one another; in steel frame construction, a *simple connection*.

Shear panel A wall, floor, or roof surface that acts as a deep beam to help stabilize a building against deformation by lateral forces.

Shear stud A piece of steel welded to the top of a steel beam or girder so as to become embedded in the concrete fill over the beam and cause the beam and the concrete to act as a single structural unit.

Shear wall A stiff wall that imparts lateral force resistance to a building frame.

Sheathing The rough covering applied to the outside of the roof, wall, or floor framing of a structure.

Shed A building or dormer with a single-pitched roof.

Sheeting A stiff material used to retain the soil around an excavation; a material such as polyethylene in the form of very thin, flexible sheets.

Sheet metal Flat rolled metal generally less than ¼ inch (6.35 mm) thick.

Shelf angle A horizontal steel angle attached to the wall or spandrel of a building to support a masonry facing.

SHGC *See* **solar heat gain coefficient**.

Shim A thin piece of material placed between two components of a building to adjust their relative positions as they are assembled; to insert shims.

Shingle A small unit of water-resistant material nailed in overlapping fashion with many other such units to render a wall or sloping roof watertight; to apply shingles.

Shiplap A board with edges rabbeted so as to overlap flush from one board to the next.

Shop drawings Detailed drawings prepared by a *fabricator* to guide the shop production of such building components as cut stonework, steel or precast concrete framing, curtain wall panels, and cabinetwork.

Shoring Temporary vertical or sloping supports of steel or timber.

Shotcrete A low-slump concrete mixture that is deposited by being blown from a nozzle at high speed with a stream of compressed air; *pneumatically placed concrete*.

Shrinkage-compensating cement Specially formulated cement, used to counteract the drying shrinkage that normally occurs during curing.

Shrinkage-reducing admixture A concrete additive that reduces drying shrinkage and the cracking that results.

Shrinkage–temperature steel *Reinforcing bars* laid at right angles to the principal bars in a one-way slab for the purpose of preventing excessive cracking caused by drying shrinkage or temperature stresses in the concrete.

Side-hinged inswinging window A window that opens by pivoting inward on hinges at or near a vertical edge of the sash.

Side jamb *See* **jamb**.

Sidelight A tall, narrow window alongside a door.

Siding The exterior wall finish material applied to a light frame structure.

Siding nail A nail with a small head used to fasten siding to a building.

Silica fume Very finely divided silicon dioxide, a *pozzolan*, used as an admixture in the formulation of high-strength, low-permeability concrete. Also called *microsilica*.

Silicone A polymer used for high-range sealants, roof membranes, and masonry water repellents.

Sill The horizontal bottom portion of a window or door; the exterior surface, usually sloped to shed water, below the bottom of a window or door.

Sill flashing *See* **sill pan**.

Sill gasket *See* **sill seal**.

Sill pan A *flashing* at the bottom of a door or window opening that captures water within the opening and directs the water back to the exterior.

Sill plate The strip of wood that lies immediately on top of a concrete or masonry foundation in wood frame construction.

Sill seal A compressible material placed between a foundation and a wood sill plate to reduce air infiltration between the outdoors and indoors.

Simple caulk and seal A method similar to the *airtight drywall approach* for constructing a light frame building enclosure that is resistant to the free flow of air, but requiring less coordination between framing and sealing operations than the airtight drywall approach.

Simple connection A steel frame connection with no usable resistance to rotation.

Single-hung window A window with two overlapping sashes, the lower of which can slide vertically in tracks and the upper of which is fixed.

Single-ply roof membrane A sheet of plastic or synthetic rubber used as a membrane for a low-slope roof.

Single-strength glass Glass approximately 3⁄32 inch (2.5 mm) thick.

Single tee A precast slab element whose profile resembles the letter *T*.

Sinker A framing nail with a slenderer shank, special coating, and other features designed for ease of driving in comparison to a traditional *common nail*.

SIP *See* **structural insulated panel**.

Sitecast concrete Concrete that is poured and cured in its final position in a building; **cast-in-place concrete**.

Skip-joist system *See* **wide-module concrete joist system**.

Skylight A glazed unit installed in a roof. Also referred to as a *unit skylight*.

Slab band A very broad, shallow beam used with a one-way solid slab.

Slab door A door that is delivered to the construction site without any attached hardware. *See also* **prehung door**.

Slab on grade A concrete surface lying upon, and supported directly by, the ground beneath.

Slag The mineral waste that rises to the top of molten iron or steel or to the top of a weld.

Slag cement *See* **blast furnace slag**.

Slaked lime *See* **hydrated lime**.

Slate A metamorphic form of clay, easily split into thin sheets.

Sliced veneer Thin sheets of wood produced by pressing a knife against a log.

Sliding window A window with one fixed sash and another that moves horizontally in tracks.

Slip-critical connection A structural steel connection in which the members are clamped together by high-strength bolts with sufficient force that the loads on the members are transmitted between them by friction along their mating (*faying*) surfaces. Also called a *friction connection*.

Slip forming Building multistory sitecast concrete walls with forms that rise up the wall as construction progresses.

Slip sheet A thin sheet of paper, plastic, or felt, placed between two materials to eliminate friction or bonding of the materials.

Slip track *See* **deflection track**.

Sloped glazing A system of metal and glass components used to make an inclined, transparent roof; in the International Building Code, glass sloped more than 15 degrees from vertical.

Slow-burn construction *See* **Mill construction**.

Slump test A test in which wet concrete or plaster is placed in a cone-shaped metal mold of specified dimensions and allowed to sag under its own weight after the cone is removed. The vertical distance between the height of the mold and the height of the slumped mixture is an index of the material's working consistency.

Slurry A watery mixture of insoluble materials with a high concentration of suspended solids.

Smelting The process of extracting pure metal from ore by the application of heat and addition of chemical reducing compounds to remove oxygen, sulfur, and other elements.

Smoke-developed rating An index of the toxic fumes generated by a material as it burns, as determined by ASTM Standard E84.

Smoke seal Materials used to resist the passage of smoke through joints or penetrations in building assemblies.

Smoke shelf The horizontal area behind the damper of a fireplace.

Soffit The undersurface of a horizontal element of a building, especially the underside of a stair or a roof overhang.

Soffit vent An opening under the eave of a roof used to allow air to flow into the attic or the space below the roof sheathing.

Soft mud process Making bricks by pressing wet clay into molds.

Softwood Wood from coniferous (evergreen) trees.

Soil Any particulate earth material, excluding rock.

Soil liquefaction A phenomenon in which a water-saturated soil loses most of its strength under the influence of sudden, large variations in loading, such as can occur during an earthquake.

Solar heat gain coefficient (SHGC) The ratio of solar heat admitted through a sheet of glass, or whole window, to the total heat energy striking the glass or window.

Solar reflectance A unitless index, ranging from 0 to 1, expressing a material's tendency to absorb or reflect solar radiation. Also called *albedo*.

Soldering A low-temperature form of *brazing*.

Soldier A brick laid on its end, with its narrow face toward the outside of the wall.

Sole plate The horizontal piece of dimension lumber at the bottom of the studs in a wall in a light frame building. Also called a *bottom plate*.

Solid-core door A flush door with no internal cavities.

Solid masonry A masonry wall without an internal vertical hollow space or cavity. *See also* **mass wall**.

Solid slab A concrete slab, without ribs or voids, that spans between beams or bearing walls.

Solid tape sealant *See* **preformed solid tape sealant**.

Solvent A liquid that dissolves another material.

Sound Absorption Average (SAA) An index of the proportion of incident sound that is absorbed by a surface, expressed as a decimal fraction of 1.

Sound Transmission Class (STC) An index of the resistance of a wall or partition to the passage of *airborne sound*, based on laboratory measurements taken according to ASTM E90.

Space truss; space frame A truss that spans with two-way action.

Spalling The cracking or flaking of the surface of concrete or masonry units, caused, for example, by freeze-thaw action, corroding reinforcing, or pointing mortars that are harder and stronger than the mortar deeper in the masonry joint.

Span The distance between supports for a beam, girder, truss, vault, arch, or other horizontal structural device; to carry a load between supports.

Spandrel The wall area between the head of a window on one story and the sill of a window on the floor above; the area of a wall between adjacent arches.

Spandrel beam A beam that runs along the outside edge of a floor or roof.

Spandrel glass Opaque glass manufactured especially for use in spandrel panels.

Spandrel panel A curtain wall panel used in a spandrel.

Span rating The number stamped on a sheet of plywood or other wood building panel to indicate how far in inches it may span between supports.

Specifications The written portion of the *construction documents* concerning the quality of materials and execution of construction procedures required for a building.

Spirit level A tool in which a bubble in an upwardly curving cylindrical glass vial indicates whether a building element is level or not level, plumb or not plumb.

Splash block A small precast block of concrete or plastic used to divert water at the bottom of a downspout.

Spline A thin strip inserted into grooves in two mating pieces of material to hold them in alignment; a ridge or strip of material intended to lock to a mating groove. In glazing, the *edge spacer* in an insulating glass unit.

Split jamb A door frame fabricated in two interlocking halves, to be installed from the opposite sides of an opening.

Spray-applied fire-resistive material (SFRM) Fibrous or cementitious insulation applied to steel or concrete with a sprayer to provide protection against the heat of fire.

Springwood In wood, the portion of the growth ring composed of relatively larger, less-dense cells. Also called *earlywood*.

Squash block Short lengths of framing lumber, inserted under points of concentrated load to prevent overloading of *I-joist* framing members.

SSP *See* **stressed-skin panel**.

Stack effect Air pressure differences within a building, caused by the tendency of warm air to rise and cooler air to fall.

Staggered truss system A steel framing system in which story-high trusses, staggered one-half bay from one story to the next, support floor decks on both their top and bottom chords.

Stain A coating intended primarily to change the color of wood or concrete without forming an impervious film.

Stainless steel A silver-colored steel alloy with superior corrosion resistance due principally to high chromium and nickel content.

Standing and running trim Door and window casings and baseboards.

Standing seam A sheet metal roofing seam that projects at right angles to the plane of the roof.

Static coefficient of friction (SCOF) The *coefficient of friction*, measured between two surfaces at rest relative to each other; used in some finish flooring slip resistance measurements. *See also* **dynamic coefficient of friction**.

Stay A sloping cable used to stabilize a structure.

STC *See* **Sound Transmission Class**.

Steam curing Aiding and accelerating the setting reaction of concrete by the application of steam.

Steel Iron with a controlled amount of carbon, generally less than 2 percent.

Steel reinforcing bars Hot-rolled, deformed steel bars used to impart tensile strength and *ductility* to concrete or masonry structures; *rebar*.

Steel trowel A metal-bladed tool used in the final stages of finishing of a concrete slab.

Steep roof A roof with a slope greater than 2:12 to 3:12 (1 in 6 to 1 in 4). A roof with sufficient slope to be made waterproof with shingles.

Sticking The cementing together of defects in marble slabs.

Stick system A metal curtain wall system that is largely assembled in place.

Stiffener plate A steel plate attached to a structural member to support it against heavy localized loading or stresses.

Stiff mud process A method of molding bricks in which a column of damp clay is extruded from a rectangular die and cut into bricks by fine wires.

Stile A vertical framing member in a panel door.

Stirrup A vertical loop of steel bar used to reinforce a concrete beam against diagonal tension forces.

Stirrup-tie A stirrup that forms a complete loop, as differentiated from a U-stirrup, which has an open top.

Stool The interior horizontal plane at the sill of a window.

Storm window A sash added to the outside of a window in winter to increase its thermal resistance and decrease air infiltration.

Story pole A strip of wood marked with the exact course heights of masonry for a particular building; used to make sure that all the leads are identical in height and coursing.

Straightedge To strike off the surface of a concrete slab using screeds and a straight piece of lumber or metal; as a noun, a long, straight item, used to perform straightedging, test the flatness of a surface, or trace a straight line.

Strain Deformation under stress; expressed as a ratio of the change in length over the original length.

Stress Force within a material, measured per unit area.

Stressed-skin panel (SSP) A panel consisting of two face sheets of wood, metal, or concrete bonded to perpendicular spacer ribs or framing members such that the panel can act as a composite structural panel.

Stretcher A *brick* or *masonry unit* laid in its most usual position, with the broadest surface of the unit horizontal and the length of the unit parallel to the surface of the wall.

Striated Textured with parallel scratches or grooves.

Stringer The sloping wood or steel member that supports the treads of a stair.

Strip flashing Membrane flashings used to seal sheet metal components to a low-slope roof membrane.

Strip flooring Solid wood finish flooring members less than 3 inches (75 mm) in width, usually in the form of tongue-and-groove boards.

Stripping Removing formwork from concrete. *See also* **strip flashing**.

Structural bond The interlocking pattern of masonry units used to tie two or more *wythes* together in a wall.

Structural composite lumber Substitutes for solid lumber made from wood veneers or wood fiber strands and glue. Also called *engineered lumber*.

Structural glazed facing tile A hollow clay masonry unit with glazed faces.

Structural glazing Glass secured to the face of a building with highly adhesive sealant or glazing tape to eliminate the need for any metal to appear on the exterior of the building.

Structural-grade plastic lumber (SGPL) Lumberlike plastic members reinforced with glass fibers and formulated to be roughly as strong as conventional solid wood.

Structural insulated panel (SIP) A panel consisting of two face sheets of wood panel bonded together by plastic foam core.

Structural lightweight aggregate Lightweight aggregate with sufficient density and strength for use in structural concrete.

Structural mill The portion of a steel mill that rolls structural shapes.

Structural standing-seam metal roofing Sheets of folded metal that serve both as decking and as the waterproof layer of a roof.

Structural terra cotta Molded components, often highly ornamental, made of fired clay, designed to be used in the façades of buildings.

Structural tubing *See* **hollow structural section**.

Structure-borne sound Sound transmitted through solid building components, such as floor slabs or structural framing, frequently referring to impact sounds transmitted through floor-ceiling assemblies and associated with *Impact Isolation Class* ratings. *See also* **airborne sound**.

Structure/enclosure joint A connection designed to allow the structure of a building and its cladding or partitions to move independently.

Stucco *See* **portland cement plaster.**

Stud One of an array of small, closely spaced, parallel wall framing members; a heavy steel pin.

Styrene-butadiene-styrene (SBS) A copolymer of butadiene and styrene used as a modifier in polymer-modified bitumen roofing.

Subcontractor A contractor who specializes in one area of construction activity and who works under a general contractor.

Subfloor The loadbearing surface beneath a finish floor.

Subpurlin A very small roof framing member that spans between joists or purlins.

Substrate The base to which a coating, veneer, or finish material is applied.

Substructure The occupied below-ground portion of a building.

Summerwood In wood, the portion of the growth ring composed of relatively smaller, denser cells. Also called *latewood.*

Sump A pit designed to collect water for removal from an excavation or basement.

Superflat floor A concrete slab finished to a high degree of flatness and levelness according to a recognized system of measurement.

Superplasticizer An admixture that makes wet concrete or grout extremely fluid without additional water.

Superstructure The above-ground portion of a building.

Supplementary cementitious material Hydraulic cementitious material or pozzolan mixed with portland cement to modify the cement product's properties or lower the energy required to manufacture the cement.

Supply pipe A pipe that brings clean water to a plumbing fixture.

Surface-bonded masonry Concrete block laid without mortar and then plastered on both sides with a fiber-reinforced cement plaster so as to make a structurally sound masonry wall.

Surface number In glazing assemblies, the distinct faces of glazing, counting from the outermost to the innermost of a glazing unit, including each face of each glazing material.

Surfacing Smoothing the surface of a material, usually by *planing.*

Suspended ceiling A finish ceiling that is hung on wires from the structure above.

Suspended glazing Large sheets of glass hung from clamps at their top edges to eliminate the need for metal mullions.

Sustainability Providing energy efficient, resource conserving, healthy buildings; *green building.*

Swedge bolt *See* **lockpin and collar fastener**.

Synthetic gypsum Chemically manufactured gypsum made from the byproducts of various industrial processes, such as the desulfurization of power plant flue gasses.

T

Tackless strip A wood strip with projecting points used to fasten a carpet around the edge of a room. Also called a *tackstrip.*

Tackstrip *See* **tackless strip**.

Tagline A rope attached to a building component to help guide it as it is lifted by a crane or derrick.

Tangential shrinkage In wood, shrinkage along the circumference of the log.

Tap To cut internal threads, such as in a hole or nut.

Tapered edge The longitudinal edge of a sheet of gypsum board, which is recessed to allow room for reinforcing tape and joint compound.

Tdw *See* **damage weighted transmittance**.

Tee A metal or precast concrete member with a cross section resembling the letter *T*.

Tempered glass Heat-treated glass that is stronger than heat-strengthened glass and is suitable for use as *safety glazing.*

Tempering Controlled heating and cooling of a material to alter its mechanical properties; a form of heat treatment.

Tendon A steel strand used for prestressing a concrete member.

Tensile strength The ability of a structural material to withstand stretching forces.

Tensile stress Internal *stress,* caused by stretching of a material.

Tension A stretching force; to stretch.

Tension-control bolt A bolt tightened by means of a splined end that breaks off when the bolt shank has reached the required tension.

Termite shield A metal flashing placed on top of a concrete foundation to prevent termites from traveling undetected from the ground into the superstructure.

Terne An alloy of lead and tin used to coat sheets of carbon steel or stainless steel; used in the past for metal roofing sheet.

Terrace door A double glass door, one leaf of which is fixed and the other hinged to the fixed leaf at the centerline of the door.

Terrazzo A finish floor material consisting of concrete with an aggregate of marble chips selected for size and color, which is ground and polished smooth after curing.

Thatch A thick roof covering of reeds, straw, grasses, or leaves.

Thermal break A material or component with low thermal conductivity installed between other, usually metal, components with higher conductivity, to retard the passage of heat through the assembly.

Thermal bridge A component of relatively high thermal conductivity that conducts heat more rapidly through an insulated building assembly, such as a steel stud in an insulated stud wall.

Thermal conduction The transfer of heat within a solid material.

Thermal conductivity The rate at which a material conducts heat.

Thermal convection The transfer of heat by the movement of air (or other fluids). Also called, simply, *convection*.

Thermal emittance A unitless index, from 0 to 1, expressing a material's tendency to radiate thermal energy as its temperature rises in relation to surrounding surfaces.

Thermal envelope *See* **building enclosure**.

Thermal insulation A material that greatly retards the passage of heat.

Thermal mass The capacity of high-density materials, such as concrete, masonry, or ceramic tile, to store heat and release it slowly over time; useful for moderating temperature extremes within a building.

Thermal radiation The transfer of heat across an air space or vacuum by electromagnetic radiation.

Thermal resistance The resistance of a material or assembly to the conduction of heat.

Thermochromic glass Glass that changes its optical properties in response to changes in temperature.

Thermoplastic In plastics, having the property of softening when heated and rehardening when cooled; weldable by heat or solvents.

Thermoplastic polyolefin (TPO) A thermoplastic single-ply roof membrane material, made from blends of polyethylene, polypropylene, and ethylene-propylene rubber polymers.

Thermosetting In plastics, not having the property of softening when heated; not heat-fusible.

Thickset tile Ceramic tile installed on a thick bed of portland cement mortar. Also called *mortar bed* or *mud set tile*.

Thin-set tile Ceramic tile bonded to a solid base with a thin application of portland cement mortar or organic adhesive.

Through-wall flashing *See* **internal flashing**.

Thrust A lateral or inclined force resulting from the structural action of an arch, vault, dome, suspension structure, or rigid frame.

Thrust block A wooden block running perpendicular to the stringers at the bottom of a stair whose function is to hold the stringers in place.

Timber A sawed wood member, rectangular in cross section, with a least nominal dimension of at least 5 inches (114 mm actual size). *See also* **board**, **dimension lumber**.

Tie A device for holding two parts of a construction together; a structural device that acts in tension.

Tieback A tie, one end of which is anchored in the ground, with the other end used to support sheeting around an excavation.

Tie beam A reinforced concrete beam cast as part of a masonry wall, whose primary purpose is to hold the wall together, especially against seismic loads, or cast between a number of isolated foundation elements to maintain their relative positions.

Tier The portion of a multistory steel building frame supported by one set of fabricated column pieces, commonly two stories in height.

Tie rod A steel rod that acts in tension.

Tile A fired clay product that is thinner in cross section than a brick: either a thin, flat element (ceramic tile or quarry tile), a thin, curved element (roofing tile), or a hollow element with thin walls (flue tile, tile pipe, structural clay tile). Also a thin, flat element of another material, such as an acoustical ceiling unit or a resilient floor unit.

Tilt/turn window A window that opens either by rotating its sash about its vertical centerline or as a hopper.

Tilt-up construction A method of constructing concrete walls in which panels are cast and cured flat on a floor slab, then tilted up into their final positions.

Timber Standing trees; a large piece of dimension lumber.

Tinted glass Glass that is colored with pigments, dyes, or other *admixtures*.

Titanium A strong, corrosion-resistant, silvery-gray *nonferrous metal*.

Toe nailing Fastening with nails driven at an angle.

Tongue and groove An interlocking edge detail for joining planks or panels.

Tooling The finishing of a mortar joint or sealant joint by pressing and compacting it to create a particular profile.

Toothed plate A multipronged fastener made from stamped sheet metal used to join members of a lightwood wood truss.

Top-hinged inswinging window A window that opens inward on hinges on or near its head.

Topping A thin layer of concrete cast over the top of a floor deck.

Topping-out Placing the last member in a building frame.

Top plate The horizontal member at the top of the studs in a wall in a light frame building.

Topside vent A water-protected opening through a roof membrane to relieve pressure from water vapor that may accumulate beneath the membrane.

Torque Twisting action; *moment*.

Torsional stress Stress resulting from the twisting of a structural member.

Touch sanded In plywood, lightly sanded to produce a smoother, flatter surface.

TPO *See* **thermoplastic polyolefin**.

Tracheids The longitudinal cells in a softwood.

Traffic deck A walking surface placed on top of a roof membrane.

Transit-mixed concrete Concrete mixed in a drum on the back of a truck as it is transported to the building site.

Travertine A richly patterned, marble-like form of limestone; classified by ASTM C119 in the Other Stone group.

Tread One of the horizontal planes that make up a stair.

Tremie A large funnel with a tube attached used to deposit concrete in deep forms or beneath water or slurry.

Trim accessories Casing beads, corner beads, expansion joints, and other devices used to finish edges and corners of a plaster wall or ceiling.

Trimmer joist A joist that supports a header around an opening in a floor or roof frame.

Trimmer stud *See* **jack stud**.

Trowel A thin, flat steel tool, either pointed or rectangular, provided with a handle and held in the hand, used to manipulate mastic, mortar, plaster, or concrete. Also, a machine whose rotating steel blades are used to finish concrete slabs; to use a trowel.

Truss A triangulated arrangement of structural members that reduces nonaxial external forces to a set of axial forces in its members. *See also* **Vierendeel truss**.

Tube Structure A building structure in which the *lateral force resisting system* is arranged continuously around the perimeter of the building frame.

Tuckpointing Traditionally, a method of finishing masonry joints using mortars of different colors to artificially create the appearance of a more refined joint; in contemporary usage, may be used interchangeably with *repointing*.

Tunnel kiln A kiln through which clay products are passed on railroad cars.

Turn-of-nut method A method of achieving the correct tightness in a *high-strength bolt* by first tightening the nut snugly, then turning it a specified additional fraction of a turn.

Two-way action Bending of a slab or deck in which bending stresses are approximately equal in the two principal directions of the structure.

Two-way concrete joist system A reinforced concrete framing system in which columns directly support an orthogonal grid of intersecting joists.

Two-way flat plate A reinforced concrete framing system in which columns directly support a two-way slab that is planar on both of its surfaces.

Two-way flat slab A reinforced concrete framing system in which columns with mushroom capitals and/or drop panels directly support a two-way slab that is planar on both of its surfaces.

Type X gypsum board A fiber-reinforced *gypsum board* used where greater fire resistance is required.

U

UF *See* **urea-formaldehyde**.

U-Factor A measure of the thermal conductance of a material or assembly; the mathematical reciprocal of *R-value*.

UHPC *See* **ultra-high performance concrete**.

Ultimate strength The maximum *stress* value reached before failure of a material.

Ultra-high performance concrete (UHPC) Concrete with an ultimate compressive strength of 17,000 psi (120 MPa) or greater.

Unbonded construction Posttensioned concrete construction in which the tendons are not grouted to the surrounding concrete.

Uncoursed stone masonry Stone masonry laid without continuous horizontal joints; random.

Undercarpet wiring system Flat, insulated electrical conductors that run under carpeting and their associated outlet boxes and fixtures.

Undercourse A course of shingles laid beneath an exposed course of shingles at the lower edge of a wall or roof in order to provide a waterproof layer behind the joints in the exposed course.

Underfire The floor of the firebox in a fireplace.

Underlayment A panel laid over a subfloor to create a smooth, stiff surface for the application of finish flooring; a water-resistant material applied under finish roofing.

Underpinning The process of placing new foundations beneath an existing structure.

Unfinished bolt An ordinary carbon steel bolt.

UniFormat The trademarked name for a system of organizing building information based on functional relationships.

Uniformly graded soil A special instance of a *poorly graded soil* in which the soil particles are mostly of one size.

Uniform settlement Subsidence of the various foundation elements of a building at the same rate, resulting in no distress to the structure of the building.

Unit-and-mullion system A curtain wall system consisting of prefabricated panel units secured with site-applied mullions.

Unit skylight *See* **skylight**.

Unit system A curtain wall system consisting entirely of prefabricated panel units.

Unreinforced Constructed without steel reinforcing bars or welded wire fabric.

Up–down construction A sequence of construction activity in which construction proceeds downward on the sublevels of a building at the same time as it proceeds upward on the superstructure.

Upside-down roof A membrane roof assembly in which the thermal insulation lies above the membrane.

Urea-formaldehyde (UF) A structural wood adhesive not suitable for exterior exposure and associated with relatively high *formaldehyde* gas emissions.

U-stirrup An open-top, U-shaped loop of steel bar used as reinforcing against diagonal tension in a concrete beam.

V

Valley A trough formed by the intersection of two roof slopes.

Valley rafter A diagonal *rafter* that supports a valley.

Vapor barrier A *vapor retarder* with a very low vapor permeability.

Vapor permeability Vapor permeance per unit of thickness.

Vapor permeance A measure of the ease with which water vapor can diffuse through a material.

Vapor pressure A measure of the pressure exerted by water molecules in a gaseous state, generally higher with higher relative humidity and higher air temperature.

Vapor retarder A material intended to resist the diffusion of water vapor into a building assembly.

Varnish A slow-drying transparent coating.

Vault An arched surface; a strongly built room for such purposes as housing large electrical equipment or safeguarding money.

Vee joint A joint whose profile resembles the letter *V*.

Vegetated roof *See* **green roof**.

Veneer A thin layer, sheet, or facing.

Veneer plaster A wall finish system in which a thin finish layer of gypsum plaster is applied over a special *veneer plaster base*.

Veneer plaster base The special gypsum board over which *veneer plaster* is applied.

Vented cladding A *drained cladding* system with an air space behind the cladding open at the bottom only. *See also* **ventilated cladding**.

Vented metal decking *Metal decking* with slotted perforations designed to allow excess moisture in the concrete cast onto the deck to evaporate downward through the decking.

Ventilated cladding A *drained cladding* system with an air space behind the cladding open at both the top and bottom. *See also* **vented cladding**.

Vent spacer A device used to maintain a free air passage above the thermal insulation in an attic or roof.

Vermiculite Expanded mica, used as an insulating fill or lightweight aggregate.

Vertical bar An upright *reinforcing bar* in a concrete column. Also called a *column bar*.

Vertical grain lumber *See* **quartersawn lumber**.

Vierendeel truss A truss with rectangular panels and rigid joints but no diagonal members. The members of a Vierendeel truss are subjected to strong nonaxial forces.

Vinyl *See* **polyvinyl chloride**.

Visible light transmittance (VT) The ratio of visible light that passes through a sheet of glass or a glazing unit to the amount of light striking the glass or unit.

Visual grading The grading of wood for its structural properties, based on visual inspection, as distinct from *machine grading*; not to be confused with *appearance grading*.

Vitrification The process of transforming a material into a glassy substance by means of heat.

Volatile organic compound (VOC) Organic (carbon-based) chemical compound that evaporates readily, is a significant air pollutant, a potential irritant to building occupants, and, in some cases, a greenhouse gas.

Volume-change joint A building separation joint that allows for expansion and contraction of adjacent portions of a building without distress.

Voussoir A wedge-shaped element of an arch or vault.

VT *See* **visible light transmittance**.

W

Waferboard A building panel made by bonding together large, flat flakes of wood.

Waffle slab A two-way concrete joist system.

Wainscoting A wall facing, usually of wood, cut stone, or ceramic tile, that is carried only partway up a wall.

Waler A horizontal beam used to support sheeting or concrete formwork.

Wane An irregular rounding of a long edge of a piece of dimension lumber caused by cutting the lumber from too near the outside surface of the log.

Warm edge spacer A glazing *edge spacer* with improved thermal resistance.

Wash A horizontal surface, sloped to drain water.

Washer A steel disk with a hole in the middle, used to spread the load from a bolt, screw, or nail across a wider area of material.

Water–cement ratio An expression of the relative proportions, by weight, of water and cement in a concrete mixture.

Waterproofing Material acting as a barrier to the flow of water and capable of withstanding hydrostatic pressure.

Water-reducing admixture Concrete *admixture* that allows a reduction in the amount of mixing water while retaining the same workability, resulting in higher-strength concrete.

Water-resistant gypsum board A *gypsum board* designed for use in locations where it may be exposed to occasional dampness.

Water-resistive barrier (WRB) A water-repellent membrane or coating used to resist the passage of liquid water through the building enclosure.

Water smoking The process of applying heat to evaporate the last water from clay products before they are fired.

Waterstop A metal, synthetic rubber, bentonite clay, or sealant strip used to seal joints in concrete foundation walls.

Water-struck brick A brick made in a mold that was wetted before the clay was placed in it.

Water table In geotechnical science, the subsurface level at which soil is fully saturated by *groundwater*; or more precisely, the level at which the pressure of water in the soil is equal to the atmospheric pressure. In architectural terms, a wood molding or shaped brick used to make a transition between a thicker foundation and the wall above.

Water vapor Water in its gaseous phase.

Water vapor diffusion The process by which water molecules in a gaseous state pass through solid materials.

Wattle and daub Mud plaster (daub) applied to a primitive lath of woven twigs or reeds (wattle).

Waxing Filling of voids in marble slabs; application of wax as a finish material.

Weather barrier *See* **water-resistive barrier**.

Weathered joint A mortar joint finished in a sloping, planar profile that tends to shed water to the outside of the wall.

Weathering steel A steel alloy that forms a self-protecting rust layer when exposed to the atmosphere.

Weatherstrip A ribbon of resilient, brushlike, or springy material used to reduce air infiltration through the crack around a sash or door.

Web A cross-connecting piece, such as the portion of a wide-flange shape that is perpendicular to the flanges or the portion of a concrete masonry unit that is perpendicular to the face shells.

Web stiffener A metal rib used to support the web of a light gauge steel joist or a structural steel girder against buckling.

Weep hole A small opening whose purpose is to permit drainage of water that accumulates inside a building component or assembly.

Weld A joint between two pieces of metal formed by fusing the pieces together by the application of intense heat, usually with the aid of additional metal melted from a rod or electrode.

Welded wire fabric (WWF) *See* **welded wire reinforcement**.

Welded wire reinforcement (WWR) A welded grid of steel reinforcing wires or bars, used most commonly for reinforcing of slabs. Also called *welded wire fabric* (*WWF*).

Welding The process of making a weld.

Weld plate A steel plate anchored into the surface of concrete, to which another steel element can be welded.

Well graded soil Coarse-grained soil with a full range of particle sizes. Also called *poorly sorted soil*.

Well sorted soil *See* **poorly graded soil**.

Wet systems Construction systems that utilize considerable quantities of water on the construction site, such as masonry, plaster, sitecast concrete, and terrazzo.

White portland cement A portland cement that is white in color; used for architectural concrete where greater color control is required.

Wide-flange shape Any of a wide range of structural steel components rolled in the shape of the letter *I* or *H*.

Wide-module concrete joist system A one-way concrete framing system with joists that are spaced more widely than those in a conventional one-way concrete joist system.

Wind brace A diagonal structural member whose function is to stabilize a frame against lateral forces.

Winder (Rhymes with "reminder.") A stair tread that is wider at one end than at the other.

Wind load A force on a building caused by wind pressure and/or suction.

Wind uplift Upward forces on a structure caused by negative aerodynamic pressures that result from certain wind conditions.

Wired glass Glass in which a wire mesh is embedded during manufacture, principally for fire resistance.

Wood–plastic composites (WPC) Woodlike products made from wood fibers, plastics of various types, and other additives, with a plastic content not exceeding 50 percent.

Wood–polymer composite planks Linear strips, intended for outdoor decking and other outdoor uses, that are made of wood fiber and a plastic binder.

Workability agent *Admixture* for concrete that improves the plasticity of wet material to make it easier to place in forms and to finish.

Working joint A connection that is designed to allow small amounts of relative movement between two pieces of a building assembly.

WPC *See* **wood–plastic composites**.

Wracking Forcing out of *plumb*.

WRB *See* **water-resistive barrier**.

Wrought iron A form of iron that is soft, tough, and fibrous in structure, containing about 0.1 percent carbon and 1 to 2 percent slag.

WWF *See* **welded wire fabric**.

WWR *See* **welded wire reinforcement**.

Wythe (Rhymes with "scythe" and "tithe") A vertical plane of masonry that is one masonry unit thick.

Y

Yield strength The stress at which a material ceases to deform in a fully elastic manner and begins to deform irreversibly.

Z

Z-brace door A door made of vertical planks held together and braced on the back by three pieces of wood whose configuration resembles the letter *Z*.

Zero-slump concrete A concrete mixed with so little water that it does not sag when piled vertically.

Zinc A relatively weak and brittle *nonferrous metal*, used most notably as a protective galvanic coating for steel.

Zoning ordinance A law that specifies how land within a jurisdiction may be used.

Index

A

AC. *See* Articulation class (AC)
Acoustic criteria
  for ceilings, 856–857
  for doors and windows, 753
  for interior finish systems, 811–813
  and laminated glass, 702, 753
Acoustic insulation, 812, 844–847
Acoustic underlayment, 867
ADA. *See* Airtight drywall approach (ADA); Americans with Disabilities Act (ADA)
Admixture
  concrete, 502–503
  mortar, 293–295
Advanced framing techniques, 199–201, 260
  and sustainability, 156
Aerogel insulation, 634
Aggregates
  coarse-grained soils, 35–36
  concrete, 497, 500–502
  grout, 318
  mortar, 293
Agrifiber panels, 106
Air and water-resistive barrier (AWB), 633, 638
  drained cladding, 632
  masonry and concrete cladding, 760, 761, 763–765
  mass timber construction, 141–142
  metal panel cladding, 803
  wood light frame construction, 212
Air barrier, 636–638
  and controlling condensation, 641
  and door and window detailing, 745
  drained cladding (rainscreen cladding), 632
  glazing, 713
  low-slope roofing, 651–656
  masonry cavity wall, 365
  masonry and concrete curtainwall, 766, 767, 771, 773
  metal and glass cladding, 794–795, 799
  in pressure-equalized design, 630–631
  steep roof, 671
  in wood light frame construction, 212, 262–264
Airborne sound, 812, 828, 837, 867
Air infiltration, 623. *See also* Air barrier
Air-moisture barrier. *See* Air and water-resistive barrier (AWB)
Air permeance, 636–638
Air-supported structures, 454, 456
Airtight drywall approach (ADA), 262–264
Air-weather barrier. *See* Air and water-resistive barrier (AWB)
Alloys, 484
  aluminum, 784–785
  copper, 486
  steel, 398, 402, 485–486
Aluminum, 486, 784–785
  alloys, 784–785
  extrusion, 785–787
  sheet metal, 679, 684
  surface finishes, 790
  sustainability, 789
Aluminum-framing and glass systems. *See* Cladding, metal and glass
American National Standards Institute (ANSI), 18
Americans with Disabilities Act (ADA), 18
Anchor bolt
  concrete, 596, 598, 611
  curtain wall, 798
  heavy timber, mass timber, 132, 136, 144, 145
  light gauge steel, 470
  structural steel, 426, 429, 430
  wood light frame, 158, 163, 168, 171, 181
Annealing, 484
  glass, 698, 699
Anodizing. *See* Aluminum, surface finishes
Apparent sound transmission class (ASTC), 812
Arches
  brick, 314–316, 323, 437
  concrete, 570
  heavy timber, 146
  steel, 449, 452
Architect, 12
Architectural sheet metal roofing, 678–684
Architectural Woodwork Institute, 748
Architecture 2030 Challenge, 8
Articulation class (AC), 857
Ash dump, 267
Ashlar stone masonry, 333, 339–341, 447, 357
Asphalt shingles, 218, 220, 657, 671–676, 685
ASTC. *See* Apparent sound transmission class (ASTC)
ASTM International, 18
Autoclaved aerated concrete (AAC), 358–359
AWB. *See* Air and water-resistive barrier (AWB)
AWI. *See* Architectural Woodwork Institute (AWI)

B

Backer rod, 644
Backfilling, 72
Ballast. *See* Roofing, low-slope, ballast
Balloon frame, 153–154
Bamboo, 85, 101, 866
  flooring, 878
Bar chart schedule. *See* Gantt chart
Bark, tree, 80–81
Barrier wall, and keeping water out, 630
  EIFS, 774–775
  masonry and concrete cladding, 767– 768
  metal panel cladding, 803
Barrier wall, for soils dewatering, 49
Basalt building stone, 332, 335, 342, 345
Base flashing. *See* flashing, low-slope roofing, base
Base isolation. *See* Seismic base isolation
Basement, 51, 52
  insulation, 70–71, 160–161
  with light wood frame construction, 156–164
  waterproofing, 65–69
Baseplate
  precast concrete column, 598
  steel column, 427, 429–431
Batten seam sheet metal roofing, 678, 683
Bauxite, 498, 784, 789
Bending moment, 415
Bessemer process, 398
BIM. *See* Building information model (BIM)
Bio-based materials, 11, 85, 114
Biocomposite panels, 106
Biodeterioration, 106
BIPV. *See* Building-integrated photovoltaic
Blast furnace slag, 502
  in cement, 502
  in concrete, 501
  in concrete masonry, 348
  in insulation, 654
  in mortar, 293
  in steel production, 458
Blast-resistant glazing system, 755
Blower door test, 263
Board foot, 94
Bolts. *See also* Anchor bolt
  concrete construction, 596–597
  heavy timber construction, 134–137
  steel construction, 410–411
  wood construction, 112

Bond, payment or performance. *See* Surety bond
Braced core, 421
Braced frame, 409, 419–421
  heavy timber and mass timber, 127, 138
  precast concrete, 588
Brake metal, 485
Brass, 486
Brazing, 485
BREEAM. *See* Building Research Establishment Environmental Assessment Method (BREEAM)
Brick flooring and paving, 302, 388, 872–873
Brick masonry, 304–318. *See also* Cladding, masonry and concrete; Masonry construction; Mortar
  ASTM classification of bricks, 302
  bonds, 305–307
  brickwork terminology, 304
  comparative material properties, 370, 390
  dimensioning, modular, 300, 307, 310
  firebrick, 266–267, 302, 315
  firing of bricks, 298–300
  fly ash bricks, 296, 300
  hollow bricks, 302, 303, 318
  laying bricks, 304–311
  molding of bricks, 297–298
  mortar joints, 310–311
    appearance, 306
    naming, 304
  preliminary design, 372
  reinforced (RBM), 318–319
  sizes and shapes of bricks, 300–301
  solid bricks, 302
  spanning openings, 312–317
  sustainability, 296
  weathering regions, 303
Bridging, 166, 168, 172
Bronze, 486
Buckling restrained bracing, 421, 446
Building codes, 13–18
  and foundations, 75
  and glass, 721–723
  and heavy timber and mass timber, 128–130
  and interior finishes, 813–816
  and interior walls, 822–823
  and light gauge steel, 482
  and masonry, 389
  and precast concrete, 611
  and steel frame, 459
  and roofing, 691
  and sitecast concrete, 575
  and wood light frame, 202–204
Building enclosure, 622–644
  foundations, 65–72
  and sustainability, 629
  wood light frame construction, 253–264
Building felt, 212–213, 632
Building information model (BIM), 26
Building-integrated photovoltaic (BIPV), 690
Building Research Establishment Environmental Assessment Method (BREEAM), 8
Building separation joint, 382–385, 809
  finish covers, 816, 817
  roofing system, 652, 665
Building wrap, 632, 636
  air permeance, 637
  vapor permeance, 640
Built-up roof (BUR), 657–660, 668

C

Cabinets, 271–274
CAC. *See* Ceiling attenuation class (CAC)
CAD. *See* Computer-aided design (CAD)
Caissons. *See* Foundations, caissons
CALGreen, 8
California Department of Public Health (CDPH) Standard Method, 816
Camber, 427
  in precast concrete frame, 586, 588, 591
  in sitecast concrete frame, 523–524
  in steel frame, 427–428
Carbon cycle, 82
Carbon dioxide
  and buildings, 4
  and cement, 500–501
  and mortar, 293, 294
  and wood, 82
Carbon fiber reinforcing, 592, 771
Carbon neutral materials, 11
Carbon sequestration, wood, 82
Carpentry
  finish, 237, 240, 265–282
  rough, 166
Carpet and carpet tile, 880–881
  and noise transmission through floors, 867
  sustainability, 866
Castellated beam, 447–448
Cast iron, 398, 485
  history, 397–398
Cavity drainage material. *See* Mortar deflection material
Cavity wall, 364–365, 632
  drainage and flashings, 376–378
  insulation, 291
  invention of, 291
  and masonry construction, 342, 364–366, 368–369, 372–374
  and masonry curtain wall, 760–765
CDHP Standard Method. *See* California Department of Public Health Standard Method (CDPH Standard Method)
Ceilings, 856–865
  acoustical, 856–858, 860–864
  with exposed structural and mechanical components, 856, 857–858
  fire-resistance rated, 865
  gypsum board and plaster, 858–859
  interstitial, 865
  suspended, 858–865
  sustainability, 866
  tightly attached, 858
Ceiling attenuation class (CAC), 857
Cellular raceway, 810, 868
Cellular steel decking, 437–438, 810, 868–869
Cellulose
  in asphalt shingles, 672
  in building and roofing felts, 212, 657
  in flooring underlayment, 867
  insulation, 254, 263, 637, 654
  in trees, 80
  in wood products, 96
Cement, 496–499
  blended hydraulic, 293, 295, 502
  hydraulic and nonhydraulic, 294, 502
  masonry, 293, 295
  mortar, 293, 295
  sustainability, 500–501
Ceramic tile. *See also* Quarry tile
  finish flooring, 872–874
  precast concrete cladding facing, 771
  slip resistance, 867
  sustainability, 866
  wall facing, 848–849
  wood light frame construction interiors, 282–284
Charring fire protection, 131–132
Chimney, 246–247, 266, 320
  framed openings for, 166, 191
Chromium, 487
  in chemical wood preservative, 107
  in stainless steel, 402, 458, 485–486
Cladding. *See also* Siding
  adjusting to movement, 623–624, 626
  drained, 229–230, 630–634
  rainscreen, 229, 632
  vented, 230, 632
  ventilated, 230, 632
Cladding, masonry and concrete
  artificial stone, 237, 760–765
  brick, 236, 237, 778–781
  exterior insulation and finish system, 375, 378, 774–776
  glass-fiber-reinforced concrete, 773–774
  precast concrete, 771–773
  prefabricated brick panels, 766
  stone, 339, 342, 364, 767–770
  stucco, 233, 236
Cladding, mass timber, 142
Cladding, metal and glass
  curtain wall, 791–799, 801
  design process, 801
  double-skin facades, 800
  metal panel, 801–803
  sloped glazing, 800
  storefront, 791–795
  sustainability, 789
  window wall, 791–796
Clay tile roofing, 324, 671, 673, 678, 691
CLSM. *See* Controlled low-strength material (CLSM)
CLT. *See* Cross-laminated timber (CLT)
CM. *See* Construction manager
Coating systems, architectural, 226
Codes, building. *See* Building codes
Coefficient of friction, 867

Cold-formed metal framing. *See* Light gauge steel frame construction
Cold-worked
  aluminum, 486, 784
  light gauge steel, 468, 469, 484
  steel, 408
Composite masonry walls, 364
Composite structural members
  metal decking and concrete, 437–439, 478
  precast and sitecast concrete, 525, 587, 607, 609
  steel and concrete beams, 437, 440
  steel and concrete columns, 457
  wood and concrete floors, 138, 143
Composition shingles. *See* Asphalt shingles
Computer-aided design (CAD), 20
Concrete, 497
  admixtures, 502–503
  aggregates, 497, 500–502
  cement, 497–499
  comparative structural properties, 509
  consolidation, 505, 543
  cracking, 506, 509, 516, 520, 522–523, 537, 538–540, 543, 566
  creep, 382, 522, 524
  curing, 497, 505–507, 537–539
  cutting, 568–569
  fastening to, 596–597
  finish flooring, 871
  formwork, 507–508
  handling and placing, 505
  history, 496–497
  hot and cold weather placement, 506–507
  innovations in, 527–529
  light transmitting, 529
  mixes, 503–505
  posttensioning, 523–527
  prestressing, 522–527
    pretensioning, 523
  pumping, 504–506
  reinforcing, 508–522
    fibrous, 520
  segregation, 505
  self-consolidating, 505
  slump test, 504, 541
  strength, 503–505
  supplementary cementitious materials, 500, 501, 502, 539
  sustainability, 500–501
  test cylinder, 504–505, 541
  ultra-high performance concrete, 503, 527, 528, 771
  water, 497, 500–501, 502
  water-cement ratio, 503, 539
Concrete blocks. *See* Concrete masonry
Concrete masonry, 348. *See also* Cladding, masonry and concrete; Masonry construction; Mortar
  ASTM classification of concrete masonry units, 348–349
  autoclaved aerated concrete (AAC), 358–359
  curing, 348
  decorative units, 354, 356, 357
  dimensioning, modular, 350
  dry-stacked, 354
  economy of, 356
  laying, 350–354
  manufacture of units, 348–350
  mortar joints, 350
  reinforcing, 354–355
  sizes and shapes of units, 348–350
  structural glazed facing tiles, 358
  structural terra cotta, 358
  surface bonded, 354
  sustainability, 343
  weights, 348–350
Concrete, precast, 584. *See also* Concrete
  assembly concepts, 588–589
  beams and girders, 586–588
  and building codes, 611
  carbon fiber reinforcing, 592
  columns, 586, 593
  composite precast/sitecast construction, 607, 609
  construction process, 621
  curtain wall panels, 771–772
  joining elements, 595–608
  lateral force resistance, 588
  manufacture, 589–595
  preliminary design, 587
  prestressing, 592
  reinforcing, 592
  shear wall, 588
    posttensioned, 598
  slabs, 586
  sustainability, 610
  transportation, 584
  wall panels, 586, 588, 595
Concrete, sitecast, 534. *See also* Concrete; Insulating concrete forms
  architectural finishes, 564–567
  and building codes, 575
  climbing formwork, 557, 572, 573, 575
  columns, 519, 521, 544–545
  economical design, 572, 575
  floor and roof systems, one-way, 545–555
  floor and roof systems, two-way, 555–560
  flying formwork, 572, 573
  form ties, 540–543, 544
  formwork costs, 572
  ganged forms, 543, 572
  innovations, 572–574
  lift-slab construction, 574, 575
  longer spans, 570–571
  posttensioned, 523–527, 561–562
  preliminary design, 574
  reshoring, 547, 549, 557
  selecting a framing system, 555, 559
  shotcrete, 564
  slab on grade, 535–540
  slip forming, 575
  tilt-up, 562, 578
  walls, 540–543
Condensation, 638
  and air barriers, 262, 623, 638
  and aluminum extrusions, 788, 794, 797
  and basement walls, 161
  and continuous insulation, 526, 641, 768
  and curtain walls, 623
  and durable wood construction, 107
  and exterior wall design, 107, 256
  and glazing, 623, 707, 743
  and light gauge steel frame construction, 481–482
  and roofs, 217–219, 652
  and sloped glazing, 800
  and vapor retarders, 261, 262, 623, 639, 640
  and windows, 732, 737, 742, 752
  and wood shingles, 671
Condensing surface, 641
Construction documents, 12, 20
Construction manager (CM), 21
Construction project delivery, 20–22
Construction type, 13–17
  mass timber (Types IV-A, -B, -C), 130
Continuous beam, 516, 518, 519, 595, 601
Continuous insulation, 161, 256, 258–259, 469, 481, 635–636
Contraction joint. *See* Control joint
Control joint (contraction joint), 382–383, 385
  concrete slab on grade, 537–539
  concrete wall, 543
  GFRC, 773
  gypsum wallboard, 842
  masonry, 349, 386
  plaster, 831–832, 834
  precast concrete toppings, 606
  terrazzo, 875
Controlled low-strength material (CLSM), 65, 74
Cool color, 656, 685
Copper, 486, 678
  sheet metal thickness, 684
Corbel
  masonry, 312–313, 320, 323
  precast concrete, 593, 601–603, 605, 613
Core structure, 23, 419, 420, 457, 576
Corner boards and trim, wood, 228, 233, 235, 237–238
Corrosion, corrosion protection
  of architectural metals, 484–487, 679
  of concrete reinforcing steel, 500, 502–503, 508, 511, 512
  of flashings, 220, 340, 378
  galvanic, 684, 686–687
  with paints and coatings, 225, 227
  of structural steel alloys, 399, 402
  of wood fasteners and connectors, 107, 109–113, 137
Cost plus a fee compensation, 22
Counterflashing. *See* Flashing, counterflashing
CPM. *See* Critical path method
Cradle-to-gate analysis, cradle-to-grave analysis. *See* Life cycle analysis
Cranes, 432–433, 628
Critical path, critical path method, 24, 25
Critical radiant flux exposure, 815
Cross-laminated timber (CLT), 97–98, 129, 138
  construction, 139–143
  sustainability, 129
Cruck frame, 127
Curtain wall. *See* Cladding, metal and glass
Cutoff wall, 45, 49
Cutting concrete, stone, and masonry, 568–569

D

d. *See* Penny
Dampproofing, 66
  foundation, 65–66, 71, 156, 162
  masonry cavity wall, 365
DCOF. *See* Dynamic coefficient of friction (DCOF)
Dead load, 34
Decking
  concrete, precast, 622–624
  concrete, sitecast, 439
  cross laminated timber, 129, 138, 148
  heavy timber, 129, 138, 144, 148
  metal, 401, 408, 437–440
  metal, vented, 654
  plastic lumber, 102
  roof, 106, 651–652
  wood, exterior, 107–108, 240–241
  wood-plastic composite, 101, 241
Declare materials disclosure, 9, 11
Deflection track, 823–824, 844, 845
Densities of building materials, 93, 339, 349, 370, 884
Design/bid/build project delivery, 20–22
Design/build project delivery, 20–23, 26
Dewatering, 49–50
Dew point temperature, 638–639, 641
Diamond cutting tools, 334, 568
Diffusion, water vapor, 217, 261, 623, 638–641, 707
Dissimilar metals and galvanic series, 113, 684, 686–687
DLT. *See* Dowel-laminated timber (DLT)
Domes
  brick, 316–317, 323
  concrete, 497, 570, 571, 574
  heavy timber, 146
  steel, 452
Door frames
  hollow metal, 748–749, 836, 845
  wood, 222, 223, 270, 271
Doors, 745, 747
  acoustic, 753
  egress and accessible, 751
  exterior residential, installation, 222–223
  fiberglass, 750
  fire, 750–751
  hardware, 751
  installation, 222–223, 751
  interior residential, 265, 269–271
  safety considerations, 752
  steel, 748–750
  structural performance, 752
  sustainability, 745
  thermal performance, 752–753
  wood, 747–748
Dowel-laminated timber (DLT), 99
  in mass timber construction, 141
Downspout, 214–215, 651, 664
Draftstopping, 815–816
Drainage, foundation, 65–66, 68, 156, 158, 160, 161
Drained cladding, 229–230, 630–632
  aluiminum and glass framing system, 794–795
  EIFS, 775
  masonry cavity wall, 365
  masonry veneer cladding, 236–237, 365, 762
  metal panel, 803
  precast concrete curtain wall, 771
  stone curtain wall, 767
  stucco, 236
  wood siding, 229
Drip, 629, 631, 632
Drywall. *see* Gypsum board
Dynamic coefficient of friction (DCOF), 867

E

Earth materials, 35–40
  for building foundations, 38–39
  cohesive, 37, 40
  drainage characteristics, 37
  frictional, 36, 37
  grading, 37–38
  loadbearing capacity, 38
  particle size, 35–36
  properties, 35–38
  stability, 35, 38–39
  subsurface exploration and testing, 39–40
  Unified Soil Classification System, 35, 36
Earth reinforcing, 72
EBD. *See* Environmental building declaration
Ecolabel, 9
Efflorescence, 295, 387
Egress system, building, 17, 751, 815
EIFS. *See* Exterior insulation and finish system (EIFS)
Electrical wiring, 246, 808, 810
  in cellular decking, 437
  in floors, 868–870
  in heavy timber construction, 139
  in light gauge steel framing, 476, 482, 845
  in light wood framing, 164, 205, 251, 253, 284
  in masonry and concrete wall construction, 378, 848
  in mass timber construction, 141, 142
  metals used for, 486
Embodied carbon, 8
Embodied energy, 9–11
Embodied water, 10
EMC. *See* Equilibrium moisture content (EMC)
Encapsulation fire protection, 130–132
Energy efficiency, 4–5, 622–623
  and air leakage, 623
  and building enclosure, 629
  and concrete thermal mass, 500
  and doors and windows, 745
  and energy codes, 17
  and foundations, 53, 70–71, 160–161, 163
  and glass, 700, 721
  and light gauge steel frame construction, 469
  and masonry thermal mass, 296, 343
  and roofing, 656
  and sustainability, 7–8
  and thermal insulation, 70
  and ventilation, 263
  and windows, 745
  and wood light framing, 262
Energy recovery ventilator, 263
Engineered lumber. *See* Lumber, structural composite
Environmental building declaration (EBD), 9, 129
Environmental labels, 9
Environmental product declaration (EPD), 9–10
  aluminum window, 745
  architectural flat glass, 700
  carpet tile, 866
  concrete, 500
  concrete masonry, 343
  corrugated steel roof and floor deck, 458
  fly ash brick, 296
  glazed curtain wall, 789
  gypsum board, 826
  insulation, 262
  limestone cladding, 343
  PVC roof membrane, 656–657
  softwood lumber, 84
  steel studs and track, 469
  structural concrete, precast, 610
  structural steel, 458
  suspended ceiling systems, 866
  vinyl tile, 866
  wood door, 745
Equilibrium moisture content (EMC), 86, 88
Ethylene tetrafluoroethylene (ETFE), 454, 700, 711, 740
Excavation, 42–49
  in up-down construction, 62, 64–65
  in wood light frame construction, 156–159
Excavation support, 42–49, 54
Expanded metal lath, 821, 825, 829, 830, 831, 833, 836
Expansion joint, 382–385. *See also* Isolation joint
  concrete slab on grade, 539
  low-slope roof, 665
  masonry veneer cladding, 760–764
  masonry wall, 376, 380–381
  metal and glass curtain wall, 795–796
  plaster, 832
Expansion of materials, thermal coefficients, 884
  masonry materials, 380
  window framing materials, 738
Exterior finishes. *See* Cladding; Paints and coatings; Siding
Exterior insulation and finish system (EIFS), 375, 378, 774–776
Exterior walls
  building code requirements, 15
  keeping water out, 629–634
  loadbearing and curtain wall, 627–628
Extrusions, aluminum, 737, 785–787

F

Fabric structures, 454–456
Fast track construction. *See* Phased construction
Fiberboard, 103. *See also* Wood panels
  cellulosic, 106, 654
  insulating sheathing, 106
  medium-density (MDF), 103
  sheathing, 185
Fiberglass reinforced plastic (FRP), 750. *See also* glass-fiber-reinforced plastic
Field impact isolation class (FIIC), 813
Field sound transmission class (FSTC), 812
FIIC. *See* Field impact isolation class (FIIC)
Fill, earth, 39, 72, 74
  controlled low-strength material, 65, 74
  engineered, 50
Finger jointed lumber. *See* Lumber, finger jointed
Finish carpentry, 19, 88, 265–281
  exterior, 125, 237–238
Fire area, 813, 822
Fire barrier. *See* Fire-rated walls and partitions
Fireblocking, 139, 153–154, 815, 876
Fire compartmentation, 813
Fire damper, 813, 865
Fire door, 704, 750–751, 822
Fire partition. *See* Fire-rated walls and partitions
Fireplace, 266–268, 282, 315
  brick, 302
Fireproofing, 442–447, 458, 575, 611, 858. *See also* Spray-applied fire-resistive materials
Fire-rated walls and partitions, 15, 813, 822–823
  fire barriers, 822
  fire partitions, 822
  fire walls, 17, 203, 389, 822
  shaft walls, 808, 822, 847
  smoke barriers and partitions, 823
Fire resistance rating, 15–17. *See also* Fire-rated walls and partitions
  of the building enclosure, 625, 628
  of brick and concrete masonry, 389
  of doors, 750
  of glass, 704
  of gypsum board and plaster partitions, 836, 837, 844, 847
  of interior walls, ceilings, and floors, 813–814
  of large wood members, 131, 142
  of light gauge steel framing, 482
  of precast concrete, 611
  of roofs, 652, 654
  of sitecast concrete, 575
  of structural steel, 16
  of wood light frame dwelling separations, 203
Fire-retardant treatments, 109
Firestopping, 813–814, 817, 837, 844, 869
Fire safing, 765, 768, 799, 814
Fire wall. *See* Fire-rated walls and partitions
Fixed-fee compensation. *See* Lump-sum compensation
  interior finish material, 814–815
  roof covering, 691
Flammability, criteria for interior finish surfaces, 814–815
Flashing
  coping, 377, 666, 667, 799
  counterflashing, 369
  EIFS, 776
  end dam, 369
  head, 221, 223
  heavy timber protection, 136, 137
  and keeping water out, 629, 632, 634
  masonry and concrete curtain wall, 760, 762–763, 765, 771, 779, 780
  masonry wall, 320, 340, 342, 365, 368–369, 376–378
  material types, 340, 342, 378, 485, 486, 744
  roofing, low-slope, 651, 662–668
  roofing, steep, 213, 214, 676
  sill, 220, 221–223, 369
  window and door, 221–223, 735, 744, 745
  Z-, 231
Flat glass, 698–700
Flat seam sheet metal roofing, 678, 682
Flooring. *See also* Decking
  acoustic criteria, 812–813, 867
  electrical resistivity, 868
  fire criteria, 813, 815
  functions of, 867–870
  preparation for, 282–283, 870
  radiant heated, 246, 252, 282
  raised access, 810, 868–870, 881
  sequence of installation, 23, 103, 470
  slip resistance, 867–868
  sustainability, 866
  thickness, 870
Fluid-applied flooring, 880–881
Fluid-applied membrane roofing, 662
Fly ash, 74
  in brick, 296, 300
  in concrete, 501, 502, 539
  in concrete masonry, 343
  in controlled low-strength material, 74
Flying formwork, 572, 573
Folded plate, concrete, 570
Footings, 50–52. *See also* Foundations
  concrete column, 544
  concrete wall, 540–541
  for light wood framing, 156, 158–161
  pressure-injected (compaction grouted), 61
  retaining wall, 74
  shallow frost-protected, 53
Forest management, 81, 82
Formaldehyde, 115
  and indoor environmental quality, 816
  and insulation products, 263
  and plastic composites, 740
  ultra-low-emitting formaldehyde, 85, 811
  and wood product adhesives, 115
  and wood product emissions, 85, 115, 811, 866
Foundations, 34–35, 50. *See also* Footings; Insulation, thermal, in foundations
  and building codes, 75
  caissons, 53–56
  deep, 53–61
  designing, 75
  loads, 34
  mat or raft, 53
  permanent wood, 164
  piles, 56–61
  radon and soil gas control, 70–72
  requirements, 34–35
  seismic base isolation, 61, 63
  settlement, 34–35, 38, 40, 74, 384, 626, 808
  shallow, 50–53
  spread, 50–53
  sustainability, 41
  underpinning, 61–64
  up-down construction, 62, 64–65
  waterproofing and drainage, 65–69, 156, 158–159
  wood light frame, 156–164
Framed wood panel, 117
Framing square, 189, 191, 192, 194, 195
Free water
  concrete, 537, 654
  wood, 86
Freeze-thaw weathering, 302, 303, 310, 339, 500, 502, 625, 762, 850
Frost-protected footings, shallow, 53
FRP. *See* Fiberglass reinforced plastic (FRP)
FSTC. *See* field sound transmission class (FSTC)
Fungi, 86, 106
Furring, 229, 378, 379, 468, 470, 823, 825

G

Gabion, 72
Gable vent, 217–218
Galvanic series for metals, 686–687
Galvanized steel, 484, 486–487, 686–687
Gantt chart, 24, 25
General contractor, 12, 20–22, 25
Geotextiles, 72
  in green roofing, 689
GFRC. *See* Glass-fiber-reinforced concrete (GFRC)
GFRP. *See* Glass-fiber-reinforced plastic (GFRP)
Glass. *See also* Glazing
  acoustic, 753
  annealed, 699
  antireflective, 711
  art, 711
  blown, 696–697
  and building codes, 721, 723
  chemically-strengthened, 711
  chromogenic (property-changing), 711
  colored, 711
  crown, 696
  cylinder, 696
  damage weighted transmittance (Tdw), 704
  double-strength, 700
  drawn, 697
  electrochromic (switchable), 711
  and energy, 721, 723
  and fading damage protection, 704
  fire-rated, 704
  flat, 698
  float, 697–698
  fritted, 704
  hazardous locations, 703
  heat-strengthened, 701

heat-treated, 699–701
history and manufacturing, 696–698
ingredients, 699
insulating, 707–709
laminated, 702
leaded, 721
lehr, 698
light, lite, 698
light to solar gain ratio (LSG), 705
low-emissivity (low-e), 708–709
mirror, 711
patterned, 711
photochromic, 711
photovoltaic, 711
plate, 697
polyvinyl butyral (PVB) interlayer, 702
punty, 696
quenching, 699
radiation-shielding, 711
reflective coated, 706
safety, 703–704
security, 755
self-cleaning, 711
silkscreened, 711
single-strength, 700
solar heat gain coefficient (SHGC), 705, 708
spandrel, 704
stained, 711
for structural use, 709–710
surface number, 709
sustainability, 700
tempered, fully tempered, 699–701
thermochromic, 711
thicknesses, 699–700
tinted, 704
U-factor, 707–708
vacuum-insulated, 707
visible light transmittance (VT), 704, 708
Glass blocks, 358
Glass-fiber-reinforced concrete (GFRC), 520, 773–774
Glass-fiber-reinforced plastic (GFRP), 738. *See also* fiberglass reinforced plastic
Glass-fiber reinforcing, 738
Glazier, 698
Glazing, 712. *See also* Glass
acoustic, 753
bite, 713
butt-joint, 713–714
double, 707–708
edge spacer, 707
fire-rated, 704, 751
large lights, 712–713
plastic, 711
safety, 703–704
single, 707, 708
sloped, 800
small lites, 712
suspended, 714, 719
triple, 707, 708
Global warming potential, 9–11. *See also* Environmental product declaration
wood, 82–83, 84
Glue-laminated wood, 96–97, 138, 144, 148
GMAX. *See* Guaranteed maximum price (GMAX)
GMP. *See* Guaranteed maximum price (GMP)
Grade beam, 52, 57, 59
Grade D building paper, 212
Grading, earth work, 39
Grading, lumber, 91–92
Grading, soil particle size, 36–38
Grain, wood, 80–83
flat, 85
vertical, 85, 87
Granite building stone, 330, 332, 333, 335–337, 339, 341, 346, 347, 359, 370, 380, 388
Green building, 5. *See also* Sustainability
Green roofs, 688–689
sustainability, 656
Groundwater, 34, 39, 40, 42, 75
Grouting, reinforced masonry, 318, 354, 355, 364
Guaranteed maximum price (GMP), 22
Gutters, 214–216, 651, 664
Gypsum, 827–828
in portland cement, 498, 499
sustainability, 826
Gypsum board, 264–265, 837, 840
as an air barrier, 262–264, 636–638
exterior sheathing, 476, 479, 632
finishing, 265, 840–844
finish levels, 844
installing, 840–844
interior finish in wood light frame construction, 245, 264–265
lath, 831, 833, 834, 836
manufacture, 837
partitions, 837, 840–847
resistance to fire, 131, 132, 827–828
roofing boards, 652, 661
sustainability, 826
trim accessories, 842
types, 840
vapor permeance, 640
veneer plaster base, 831, 833, 834
Gypsum plaster, 264, 827–828, 834, 836, 837, 838–839
Gypsum underlayment. *See* Underlayment, flooring, self-leveling

H

Hardboard, 106. *See also* Wood panels
Hardwoods, and softwoods, 80–82
HDO plywood. *See* Plywood, high-density overlay
Head flashing. *See* Flashing, head
Health product declaration (HPD), 10, 11
Heating, ventilation, and air conditioning (HVAC), 808
forced air, 250
hydronic, 172, 246, 251, 252
radiant, 246, 252
Heat recovery ventilator, 263
Heat treatment
aluminum, 486, 784–785
glass, 699–701
metal, 484
steel, 402, 410, 484
Heavy timber frame construction, 126, 127, 130
accommodating building services, 139
anchoring beams to walls, 133
and building codes, 128–130
as fire-resistive type IV construction, 128–129
floor and roof decks, 138
historical evolution, 126–128
lateral stability, 139
longer spans in, 144–147
with masonry wall construction, 372
minimum member sizes, 129
partition framing, 138
preliminary design, 148
sustainability, 129
in type V construction, 129, 130
with wood-concrete composite construction, 143
and wood shrinkage, 134, 135
Height and area limitations, building code, 13–17
Helical pile, 60
High-density overlay plywood. *See* Plywood, high-density overlay
High-performance concrete (HPC), 503
Hold-down, 183, 184
Hose stream test, 813
Housewrap, 212–213, 262
vapor permeance, 640
HPD. *See* Health product declaration (HPD)
Humidity, relative, 638, 639, 641
and wood moisture content, 86, 94
HVAC. *See* Heating, ventilation, and air conditioning (HVAC)
Hydrated lime. *See* Lime, hydrated

I

IAQ. *See* Indoor air quality (IAQ)
Ice barrier, ice and water shield. *See* Roofing, steep, ice barrier
Ice dam. *See* Roofing, steep, ice dam
ICF. *See* Insulating concrete forms (ICF)
I-joist, 101, 166, 167, 169, 172–174, 188, 196, 202
preliminary design, 202
Impact isolation class (IIC), 812–813
Incentive provision, 22
Incised wood, 107, 108
Indoor air quality (IAQ)
and air leakage, 623, 629, 636
and carpet and resilient flooring, 880
and formaldehyde, 115
and interior finishes, 811, 816
and interior sealant joints, 644
and paints and other coatings, 224, 240
Indoor environmental quality, 816. *See also* Indoor air quality
Insulating concrete forms (ICF), 164, 563–564, 575
Insulation, acoustic. *See* Acoustic insulation
Insulation, thermal. *See also* Exterior insulation and finish system (EIFS); Insulating concrete forms
in the building enclosure, 623, 629, 634–636, 641

comparative material properties, 254, 654
continuous, 256, 258, 259, 635–636, 641
in foundations
large buildings, 70–71
small buildings, 160–161, 163
in light gauge steel framing, 469, 481
in masonry and concrete cladding, 760–763, 764–765, 766–768, 770, 771
in masonry wall construction, 367, 372–375, 378–379
in metal cladding, 632–633, 803
in precast concrete, 588, 595
in roofing, low-slope, 651, 652–654, 655, 656, 689
in roofing, steep, 216–219, 259
in tilt-up concrete, 562
in wood light framing, 253–260
Integrated project delivery (IPD), 26
Interior finishes. *See also* Ceilings; Interior walls and partitions
fire criteria, 813–816
relationship to mechanical and electrical services, 246, 808–810, 816
selection criteria, 811–817
sustainability, 810
trends in, 817–818
in wood light framing, 264–284
Interior walls and partitions. *See also* Fire-rated walls and partitions
facings, 848–850
fire criteria, 813–814, 822–823
framing, 823–825
gypsum board, 837–847
masonry, 848
plaster, 827–837
Interlayer, laminated glass, 702, 704, 710
Intermediate seismic force resisting system. *See* Seismic force resisting system
International Building Code (IBC), 13–17
International green construction code, 8
International residential code (IRC), 17
Intumescent coatings, 109, 225, 444, 447
IPD. *See* Integrated project deliver
IRC. *See* International Residential Code
Iron. *See* Cast iron; Wrought iron
Iron ore, 396, 398, 400, 458, 484
Isolation joint, 382, 383
concrete slab on grade, 535, 536, 539
concrete wall, 543
masonry wall, 380
ISO 14020 standards, 9

J

Joints in buildings, 382–385. *See also* Building separation joint; Control joint; Expansion joint; Isolation joint
and keeping water out, 630–634
sealing, 641–644
Joist, wood, 153, 155, 166–169, 171–172, 187–188, 190, 192–193, 202. *See also* I-joist
JUST materials disclosure, 12

L

Laminated strand lumber (LSL), 100, 101
Laminated veneer lumber (LVL), 95, 97, 100, 101, 147, 173, 736
Lateral force resisting system (LFRS), 142, 182, 409, 419–421, 463. *See also* Lateral stability, building
Lateral stability, building. *See also* Lateral force resisting system, Seismic force resisting system
and foundations, 34
in heavy timber construction, 138, 139
in light gauge steel frame construction, 473
in masonry wall construction, 365
in mass timber construction, 142
in precast concrete framing systems, 588
in sitecast concrete construction, 555, 559
in steel frame construction, 419–421
in wood light frame construction, 181–186
Lath, 827, 831
expanded metal, 820, 821, 825, 829, 830–831, 833, 834, 836, 837, 849, 859
gypsum, 831, 833, 834, 836
for stucco and artificial stone, 236, 237
veneer plaster base, 831, 833, 834, 836
LCA. *See* Life cycle analysis (LCA)
Leads for masonry walls, 307–309, 351–353
Lean construction, 26
LEED, 6–8, 11, 12, 85, 226, 240, 263, 685, 731, 812. *See also* Sustainability
Lewis, 335, 341
LFRS. *See* Lateral force resisting system
Life cycle analysis (LCA), 9–10, 11
Lift-slab construction, 574, 575
Light gauge steel frame construction, 468. *See also* Ceilings, suspended
advantages and disadvantages, 482
and building codes, 482
concept, 468–470
finishes for, 482
framing, backup for cladding or veneer, 479–480, 483, 764–765, 773, 803
framing, partition, 823–825
framing, structural, 470–479
insulating, 481–482, 635–636
preliminary design, 481
standard shapes and sizes, 468–470
sustainability, 469
thicknesses of members, 469
Lime, 293
in autoclaved aerated concrete, 358–359
in cement, 497
in glass, 699
in gypsum plaster, 827–828, 838
hydrated, 293
in mortar, 290, 293–295, 343
in portland cement plaster, 827, 828–829
slaked, 293
and steel production, 399, 400
Limestone
building stone, 291, 330, 332, 333, 339, 340, 342, 343, 370, 380, 768, 770, 850
in the manufacture of lime, 290, 293
in portland cement, 496, 497, 501
in steel production, 398–400
sustainability, 343, 458, 501
Linoleum, 878, 879
sustainability, 866
Lintel, 312, 354, 408
brick masonry, 289, 312, 313, 321, 369, 373
concrete masonry, 349, 354–355, 369, 373
fireplace, 267
Liquefaction. *See* Soil liquefaction
Liquid limit, of soil, 36, 37, 40
Live load, 34
Living building challenge, 5, 8, 11, 12, 85, 240, 263, 657, 661, 741, 816
Locally sourced (regional) materials, 11, 263, 296, 343, 458, 588, 810
LSL. *See* Laminated strand lumber
Lumber, plastic, 102, 109, 741
Lumber, 84. *See also* Wood
defects, 90–91
dimensions, 93–94
finger jointed, 96, 97, 98, 101
grading, 91–92
sawing, 84–86
seasoning, 86–89
structural properties, 93
surfacing, 89
Lumber, structural composite, 98, 100, 115
in heavy timber and mass timber construction, 126, 129, 145
in windows and doors, 745
in wood light frame construction, 167, 169, 176, 177, 178. *See also* I-joists; Laminated strand lumber (LSL); Laminated veneer lumber (LVL); Parallel strand lumber (PSL)
Lump-sum compensation, 22
LVL. *See* Laminated veneer lumber

M

Magnesium, 487, 501, 687, 784
Mantels, 277, 282
Manufactured home, 117, 118
Marble building stone, 291, 330, 332, 333, 335, 339, 340, 370, 380, 850, 871, 873
Masonry construction. *See also* Brick masonry; Concrete masonry; Mortar; Stone masonry
acoustic properties, 389
and building codes, 372, 389
cavity walls, 364–370, 373, 374, 376–378, 632, 760–765
cold-and hot-weather construction, 295, 387
comparative material properties, 339, 349, 370, 380, 389, 390
composite walls, 364, 366, 368
efflorescence, 295, 387
expansion and contraction, 380, 382, 624–625, 762
fire resistance, 350, 389
in fire-resistive heavy timber construction, 128, 129, 132–133, 372

flashing and drainage, 368–370, 376–378
history, 290–293
insulation, thermal, 367, 373–375, 378–379
joint reinforcing, 354, 366, 367, 373, 374, 380
joints in wall construction, 380–386
loadbearing walls, 318–319, 331, 364, 365, 368, 371, 372, 373–375
moisture resistance, 387
paving, 388, 872, 873
preliminary design, 372
reinforced walls, 365–368
spanning systems, 372–375
ties, 364, 365–367
uniqueness, 389
unreinforced walls, 318, 319, 320, 359, 365, 390
Mass plywood panel, 98
Mass timber, 126
and building codes, 130
construction, 140–143
fire-resistance, 130–132, 142
sustainability, 129
Mass wall, 630
MasterFormat, 18–20
MDF. *See* Fiberboard, medium-density
MDO. *See* Plywood, medium-density overlay
Means of egress, building, 17
Mechanical and electrical services, 246–253, 808–810
within ceilings, 810, 858, 862
exposed, 139, 816, 857–858
within floors, 868–870
Mechanically stabilized earth, 72
Medium-density fiberboard (MDF). *See* Fiberboard, medium-density
Medium-density overlay plywood (MDO). *See* Plywood, medium-density overlay
Membrane fire protection, 445, 858, 865
Metal decking. *See* Steel frame construction, metal decking
Metal heat treatment
annealing, 484
quenching, 402, 484
tempering, 402, 484
Metal lath. *See* Expanded metal lath
Metals in architecture, 484–487
See also dissimilar metals and galvanic series
Metric unit conversions, 885
Mill construction, 128, 132, 133, 372
Millwork and finish carpentry, 245, 265–282
exterior, 237–238
Minimum critical radiant flux exposure, 815
Modified bitumen membrane roofing, 658–660
Modular construction, 117–118, 121–123
sustainability, 156
Moisture barrier. *See* Water resistive barrier (WRB)
Moisture content
earth materials, 35–38, 74
interior finish carpentry, 265
wood, 86–89, 106
Moldings
exterior, 237
fiberboard, 103
interior, 272, 277, 279, 876
plaster, 838, 839
Moment-resisting frame, 419, 421, 555, 588
Mortar, 293
admixtures, 295
ASTM types, 294, 295
cement-lime, 293, 295
cement types for, 293
hydration, 294–295
ingredients, 293–294
joint deterioration, 387
joint repointing, 387
joint thickness and profiles, 310, 315
joint tooling, 310, 311
lime, 294
mixes, 294
tuckpointing, 387
Mortar deflection material, 365, 370, 763
Movement joint. *See* Joints in buildings
Mud slab, 65, 68

N

NAF. *See* No added formaldehyde (NAF)
Nails, 109–111
for chemically-treated wood, 107, 110
and development of light wood frame construction, 153
exterior siding, 109, 228, 230, 231
finish carpentry, 109, 270–272
standard nailing for platform frame construction, 170–171
Nail flanged window, 222, 744
Nail-laminated timber (NLT), 99
in mass timber construction, 126, 138, 141
National Building Code of Canada, 13, 130, 262, 753
National Green Building Standard, 8
Needling, 63
NLT. *See* Nail-laminated timber (NLT)
No added formaldehyde (NAF), 85, 115
Noise reduction coefficient (NRC), 812, 856
NRC. *See* Noise reduction coefficient (NRC)

O

Occupancy, building code, 13, 14, 822
Occupational Safety and Health Act (OSHA), 18
OITC. *See* Outdoor-indoor transmission class (OITC)
Omniclass, 20
Open-web steel joists (OWSJs), 401, 408–409, 435, 460, 857
Optimum value engineering. *See* Advanced framing techniques
Ordinary construction, 363, 372
Ordinary seismic force resisting system. *See* Seismic force resisting system
Oriented strand board (OSB), 101, 103, 105, 106, 115, 117. *See also* Wood panels
air permeance, 637
fireblocking, 815
vapor permeance, 640
in wood light frame construction, 156
Oriented strand lumber (OSL), 100, 736
OSB. *See* Oriented strand board (OSB)
OSHA. *See* Occupational Safety and Health Act
OSL. *See* Oriented strand lumber (OSL)
Our Common Future, 4, 5
Outdoor-indoor transmission class (OITC), 625, 753

P

Paints and coatings, 224–227
sustainability of, 240
Panelized construction, 117
Parallel strand lumber (PSL), 100, 143, 177
Parapet coping, 667
Parapet flashing. *See* Flashing, parapet
Particleboard, 103, 115, 185, 282, 740, 815, 879, 185. *See also* Wood panels
Partitions. *See also* Interior finishes
demountable, 846
fire criteria, 15, 16, 813, 814, 822–823
framing, 823–825
gypsum board, 837–847
masonry, 848
plaster, 827–837
Passive house standard, 8, 257
Payment bond, 22
Penny (d), 109–110
Performance bond, 22
Perimeter insulation, 70, 71
Permeable unit paving, 388
Phased (fast track) construction, 21, 22–23
Phenol-formaldehyde, 115, 263
Piles. *See* Foundations, piles
Pill test, 815
Pitch (sound), 812
Plainsawn lumber, 84–87, 89
Plainsliced veneer, 95
Plaster and plastering. *See also* Lath
ground, 825, 831, 832, 834, 837
gypsum, 264, 443, 827–829, 834, 836–839, 851
on gypsum lath, 833, 834, 836, 837
history, 827
on masonry, 825, 827, 833, 834–835, 848
on metal lath, 821, 829, 833–834, 836, 837, 851
ornament, 838–839
portland cement (stucco), 233, 236–237, 828–829, 834
resistance to fire, 827–828, 834, 837
textures, 827, 829, 834, 837, 838
trim accessories, 831–833, 834, 836, 837
veneer, 265, 831, 833–837
Plastic glazing, 711, 752
Plastic limit, of soil, 40
Plastic lumber, 102, 109. *See also* Wood plastic composite (WPC)
Plastics in building construction, 739–741

Platform framing, 153, 154–156, 164–199, 204, 205. *See also* Wood light frame construction
Plumbing
  commercial, 808–810
  residential, 246–249
Plywood, 103. *See also* Wood panels
  Exposure 1, 105, 106, 115
  Exterior, 105
  hardwood, 106, 115, 265
  high-density overlay (HDO), 105
  medium-density overlay (MDO), 103
  production, 103–105
  veneer grades, 105
PMR. *See* Protected membrane roof (PMR)
Pneumatic structure, 454
Poke-through fittings, 868, 869, 905
Polyvinyl butyral (PVB), 702, 710, 754, 906
Porous unit paving. *See* Permeable unit paving
Portland cement, 293, 496. *See also* Cement
Portland cement plaster. *See* Stucco
Postconsumer recycling. *See* recycling, poastconsumer
Powder coating, 225, 790
Pozzolan, 502
Precast concrete. *See* Concrete, precast
Preconsumer recycling. *See* recycling, preconsumer
Prefabrication
  aluminum and glass framing, 791, 793
  brick panel cladding, 766
  exterior wall panels, 628
  factory-built housing, 117–118
  mass timber components, 96–99
  modular construction, 121–123
  shear panels, 186
  steel components, 426–428
  steel, light gauge, components, 470, 473
  stone panel cladding, 769
  wood panels, 117, 201
  wood trusses, 115, 201, 202
Preservative treated wood, 72, 97, 107–108, 164, 166, 168, 171, 229. *See also* Wood treatments
Pressure-equalized design, 630, 631, 634
  in cladding joints, 771
  in curtain walls, 794
  in glazing, 713
  in masonry walls, 378
Pressure-treated wood, 107–109
Prestress, concrete, 497, 522–527
Product data sheet (PDS), 8, 9
Protected membrane roof (PMR), 652, 653, 655, 656, 658, 688
Protection board, 68, 71, 158
PSL. *See* Parallel strand lumber (PSL)
PVB. *See* Polyvinyl butyral (PVB)

Q

Quarry tile, 315, 537, 872, 874
Quartersawn lumber, 85, 91
Quartersliced veneer, 83, 95
Quartz building stone, 332
Quicklime, 293
Quoins, 322

R

Radiant heat barriers, 260–261, 636
Radon gas, 41, 70–72, 156
  Rafter, wood, 153, 155, 190–196, 202
Rainscreen cladding. *See* Drained cladding
Rammed aggregate pier, 45, 61, 62
Rapidly renewable materials, 8, 11, 101, 102, 263, 810, 866
RBM. *See* Brick masonry, reinforced
Recycling, 10, 11, 810
  of aluminum, 789
  of brick masonry materials, 296
  closed-loop, 866
  of concrete materials, 500, 529
  of floor and ceiling products, 866
  of glass and plastic glazing, 700
  of gypsum board, 826
  in insulation products, 254, 262, 263
  of large wood members, 84, 129
  in paint, 240
  of plastics, 741
  in plastic lumber, 102
  preconsumer, 10–11
  postconsumer, 11
  of roofing materials, 656, 657
  of steel scrap, 399, 458, 469
  of stone and concrete masonry materials, 363
  of windows and doors, 745
  in wood and fiberboard panel products, 102, 106
  in wood-plastic composites, 101
Regional materials. *See* Locally sourced materials
Relative humidity. *See* Humidity, relative
Resilient flooring, 103, 282, 283, 285, 538, 741, 867, 878–879, 880
  sustainability, 656, 566
Retaining walls, 72–75, 240, 318, 355
Ridge beam, 190, 471
Ridge board, 154, 155, 170, 190–193, 473
Riftsliced veneer, 95
Rivet, 485. *See also* Timber rivet connectors
  structural steel, 409
Rock anchors, 48, 49, 72
Roll roofing, 672
Roofing. *See also* Roofing, low-slope; Roofing, steep
  and building codes, 691
  and the building enclosure, 622
  cool, 656, 660, 661, 684–685
  fire criteria, 691
  green, 656, 688–689
  and keeping water out, 629
  and photovoltaic systems, 690–691
  sustainability, 656–657
Roofing felt, 212, 217, 220, 656–658
  air permeance, 637
Roofing, low-slope, 651
  air barrier, 654–656
  ballast, 652–653, 658, 660
  decks, 651–652
  details, 662–668
  drainage, 662–668
  insulation, 652–654
  membranes for, 657–662
  minimum slope, 651
  ponding, 652
  structural metal panel, 669–670
  traffic decks, 662
  vapor retarders, 653, 655–657
  ventilation, 652, 653
Roofing, steep, 213, 671
  architectural sheet metal, 678–684
  decks, 672
  eaves and rakes, 213–214
  gutters and downspouts, 214, 215
  ice barrier (ice and water shield), 213, 217, 218, 220, 671, 674
  ice dam, 215–218, 671, 674
  minimum slopes, 671
  shingles, 220, 671–677
  skip sheathing, 671
  underlayment, 212
  unventilated, 218–219
  ventilated, 216–218
Room fire growth contribution, 815
RSI-value, 253, 634. *See also* R-value
  conversion to U.S. customary units, 885
Rubberized underlayment. *See* Roofing, steep, ice barrier
Rubber, synthetic, 739, 740
Rubble stone masonry, 333, 339–341
R-value, 253, 634
  of example wood framed walls, 258–259, 635
  of glazing units, 708
  of insulating materials, 254, 634
  of example light gauge metal framed walls, 636
  of rigid roofing insulation materials, 654

S

SAA. *See* Sound absorption average (SAA)
Safing. *See* Fire safing
SCOF. *See* Static coefficient of friction (SCOF)
Screw slots and screw ports, 785, 787, 797
Screws, wood and lag, 111, 112
Scupper, 132, 663, 664
Sealants and sealant joints, 642–644
  in exterior wood light frame construction, 238
Secant wall, 47
Seismic base isolation, 61, 63
Seismic force resisting system (SFRS), 421. *See also* Lateral force resisting system; Lateral stability, building
  and heavy timber construction, 137, 139
  and structural steel welds, 413

Seismic fuse, 421
Self-adhering flashing. *See* Flashing, self-adhered
Self-leveling underlayment. *See* Underlayment, flooring, poured gypsum or portland cement
Sequential construction, 22, 23
Sequestered carbon, 82–84
SFRM. *See* Spray-applied fire-resistive materials (SFRM)
SFRS. *See* Seismic force resisting system
Shaft walls. *See* Fire-rated walls and partitions
Shear block, 785, 787, 797, 798
Shear core, 420, 421
Shear walls
  in heavy timber construction, 139
  in mass timber construction, 142
  in precast concrete construction, 588, 598, 599
  in steel frame construction, 419–421
  in wood light frame construction, 165, 181–183, 185, 186
Sheeting, sheet piling, 42–44, 49
  bracing of, 47
Sheet metal. *See* Metals in architecture
Sheet metal flashing. *See* Flashing
Sheet metal roofing. *See* Architectural sheet metal roofing
Shotcrete, 43, 44, 47, 564
  Siding
  artificial stone, 237
  fiber-cement panel, 237
  masonry veneer, 236–237
  metal and plastic, 232–233, 235
  plywood, 105, 106, 231
  rainscreen, 229, 230
  shingle, 231–234
  stucco, 233–236
Sill flashing *See* flashing, sill
Sill pan, 220, 222, 744
Sill seal, 168, 171, 264
Single-ply membrane roofing, 220, 656, 657, 660–662
Single-purpose entity, 22, 26
SIP. *See* Structural insulated panel (SIP)
Slab on grade, concrete, 51, 52, 535
  casting, 535–540
  insulation, 70, 71, 161
  joints, 535–539
Slaked lime. *See* Lime, slaked
Slate building stone, 332, 850, 871, 873
Slate roofing, 657, 672,673, 677
Slip resistance of floors, 867–868
Slip track. *See* deflection track
Slope support. *See* Excavation support
Slump test, 504, 541
Slurry wall, 45–47, 49, 54, 64
Smelting, 398, 784, 789
Smoke barriers and smoke partitions. *See* Fire-rated walls and partitions
Smoke-developed rating, 814
  Smoke seal, 765, 768, 771, 799
Soffit vent, 217, 218
Softwoods, and hardwoods, 80–81
Soil gas, 41, 70–72, 156
Soil liquefaction, 36, 38, 40, 44, 61
Soil mixing, 44–46, 49, 72
Soil nailing, 48, 72
Soils. *See* Earth materials
Soil testing, 39–40, 75
Soldering, 222, 485, 678, 682
Soldier beams and lagging, 42–44
Sound absorption average (SAA), 812, 856
Sound attenuation blanket. *See* Acoustic insulation
Sound pitch, 812
Sound transmission class (STC), 812–813
  of the building enclosure, 625
  of doors and windows, 753
  of gypsum board partitions, 844, 847
  of masonry walls, 389
  of plaster partitions, 814, 836, 837
Space frame
  concrete, 570
  steel, 449, 451
Special seismic force resisting system. *See* Seismic force resisting system
Specifications, 12, 19
Split-ring connector, 112, 113, 133, 135, 137, 140, 144, 145
Spray-applied fire-resistive materials (SFRM), 443–446
Stack effect, 636, 637
SSP. *See* Stressed-skin panel (SSP)
Staggered truss, 441, 449
Stainless steel, 402, 485–486
Stains, 225, 227
Stair
  concrete
    cast in place, 567
    precast, 612, 614–616
  enclosure, fire-rated, 750, 813, 847
  finishes, fire criteria, 815
  glass, 694, 695, 702, 710
  opening
    steel framed, 426
    wood framed, 166, 172, 189
  proportioning, 280–281
  steel, 408
  terminology, 275–277
  wood, 273, 275–278
Standard for the Design of High-Performance Green Buildings, 8
Standing seam sheet metal roofing, 678–681
Static coefficient of friction (SCOF), 867
Steel, 398–409. *See also* steel frame construction
  alloys, 402, 485
  cast steel, 408
  cold-worked steel, 408, 484
  steelmaking, 398–402
Steel frame construction. *See also* Open-web steel joists
  arches, 449–452
  architectural structural steel, 440, 442
  bolts, 410–411
  and the building codes, 459
  castellated beam, 447, 448
  comparative structural properties, 459
  composite construction, 408, 437–440
  concrete decks, 439
  connections, beam-to-column, 415–418, 421–424
  connections, column, 421, 425, 430
  erector, 428–437
  fabricator, 426–428
  fire protection, 442–447
  framing plan, 426
  history, 396–398
  lateral stability, 419–421
  metal decking, 437–440
  plate girders, 447
  preliminary design, 401
  rigid frames, 449
  rivets, 409
  roof decking, 437–440
  shear and moment connections, 415, 421
  space frame, 449, 451
  structural shapes, 402–408
  sustainability, 458
  tensile structures, 452–453
  trusses, 447–451
  trusses, staggered, 441, 449
  uniqueness, 459
  welding, 411–415, 418, 422–425, 427, 428–431, 435, 437
Steel studs, 468–470, 481, 823–824. *See also* Light gauge steel frame construction
Steiner tunnel test, 814, 815
Stone cladding. *See* Cladding, masonry and concrete, stone
Stone flooring, 871, 873
Stone masonry, 330. *See also* Cladding, masonry and concrete, stone
  anchoring, 342, 364, 365
  comparative physical properties of stone, 339
  mortar joints, 339–340
  quarrying and milling of stone, 332–335
  sealant joints, 340
  selecting stone for buildings, 335
  stonework, 335–342
  sustainability, 343
  types of building stone, 330–332
Stone wall facing, 332, 850
Stressed-skin panel (SSP), 117
Stripping. *See* Flashing, low-slope roofing, strip
Structural composite lumber. *See* Lumber, structural composite
Structural insulated panel (SIP), 117
Structural panel metal roofing, 669–670
Structure borne sound, 812, 867
Stucco, 223, 236, 237, 359, 382, 387, 828–829, 834
Stud, wood, 153–156, 176–181, 202
Subcontractor, 4, 12, 19, 20, 21
Substructure, 19, 38, 40, 43, 46, 49, 50, 52–54, 62, 65, 66, 72, 74, 75, 622, 912
Subsurface exploration, 39–40, 75
Superinsulation, 257
Superstructure, 50, 52, 54
Surety bond, 22
Surface number. *See* Glass, surface number
Sustainability, sustainable development, 4–5

T

Tangent wall, 47, 65
Tensile structures, 34, 452, 454, 456, 720
Termination bar, 67, 666
Terra cotta, 323, 346, 358, 364, 627, 855
Terrazzo, 343, 359, 537, 815, 817, 818, 871, 875–876
Thatch (roofing), 650, 651
Thermal break
  aluminum window extrusion, 737, 743, 788–789
  curtain wall, glass, 795, 797
  exterior wall furring, 142, 803
  in insulating glass unit spacers, 707
  in light gauge steel frame construction, 458
  sloped glazing, 800
  steel and bronze window, 742, 743
  steel shelf angle, 762
Thermal bridging, 635
  in concrete masonry, 379
  in EIFS, 774
  and energy performance, 629
  in exterior wall furring, 632
  in light gauge steel construction, 469, 481, 482, 635–636
  in masonry veneer curtain wall, 762, 765
  in metal roofing, 670
  in wood light frame construction, 161, 200, 256–260
Thermal conduction, 253, 623, 634
Thermal convection, 623, 800. *See also* Stack effect
Thermal expansion of materials. *See* Expansion of materials, thermal coefficients
Thermal insulation. *See* Insulation, thermal
Thermal mass
  and brick masonry, 296
  and concrete construction, 500
  and masonry wall construction, 378
  and stone and concrete masonry, 343
Thermal radiation, 636
  in wood light frame construction, 260
Thermal resistance. *See* R-value
Thermoplastic materials, 771, 739–741
  roof membranes, 656, 660, 661, 662
Thermosetting materials, 739–741
  in metal composite material panels, 802
  powder coatings, 484, 790
  single-ply roof membranes, 656, 660–663
Tile. *See* Ceramic tile; quarry tile
Tilt-up construction. *See* Concrete, sitecast, tilt-up
Timber frame construction. *See* Heavy timber frame construction
Timber rivet connector, 112, 137
Tin, 484–487, 679, 698
Titanium, 487, 678, 679, 698, 801, 802
Toothed-plate connectors, 109, 113, 115, 116
Traffic coating, 880
Travertine building stone, 332, 342
Trees, 80–83
  and carbon, 83
  and environmentally certified wood, 81
Trusses. *See also* open-web steel joists
  heavy timber, 137, 145, 148
  light gauge steel, 473, 477–479
  sitecast concrete, 570
  steel, structural, 401, 441, 447, 449–451
  wood light frame, 115–116, 173, 201, 202
Tube structure, 420, 421, 463
Tuckpointing, mortar joint, 387
Turnkey construction, 22

U

U-factor
  glazing, 707, 708
  window, 743, 752, 753
UHPC. *See* Ultra-high performance concrete (UHPC)
Ultra-high performance concrete (UHPC), 503, 527, 528, 771
Underfloor services, 868–870
Underlayment, flooring. *See also* Acoustic underlayment
  cement panel, 874
  poured gypsum or portland cement, 282, 283, 870
  wood and fiberboard panel, 103, 105, 106, 188, 282, 870, 876, 878–880
Underlayment, roofing. *See* Roofing, steep, ice barrier; Roofing, steep, underlayment
Underpinning, 61–64, 75
Uniformat, 19, 20
Unit conversions, 885
Up-down construction, 62, 64–65
Urea-formaldehyde, 115, 866

V

Vacuum-insulated glazing, 707
Vacuum insulation board, 634, 654
Vapor barrier, 261, 639, 707, 737. *See also* vapor retarder
Vapor diffusion, 261, 623, 638–641
Vapor diffusion port, 217
Vapor permeability, vapor permeance, 261, 262, 639, 640
Vapor retarder, 639–641
  Class I, II, and III, 261, 639
  with concrete slab on grade, 66, 71, 156, 158, 160, 161, 535, 536
  crawlspace, 160
  and deterioration of paints and coatings, 226
  and durable construction, 107
  in low-slope roofing, 651, 655–657
  in steep roofing, 671
  with wood flooring, 876
  in wood light frame construction, 255, 261–262
Vault
  brick masonry, 315–317, 324
  concrete, 570
  gypsum board, 856, 858
  heavy timber, 146
  historic masonry and concrete, 291, 292, 396
  horizontal thrust, 34
  plaster, 856
  stone masonry, 345
  structural steel, 452
Veneer plaster, 265, 833–836
Veneer, wood, 83, 95, 106, 265
Vented cladding, 230, 632
Ventilated cladding, 230, 632
Vent spacers (roof), 214, 216, 217, 255, 256
Volatile organic compound (VOC, 9, 11)
  and ceiling and floor finishes, 880, 881
  and insulation materials, 263
  and interior finishes, 811, 816, 826
  and joint sealants, 644
  in paints and coatings, 9, 224, 240
  in roofing materials, 657

W

Water-cement ratio (w-c ratio), 503, 539
Waterproofing, foundation, 65–69, 156, 158, 160–163, 630
Water repellents, masonry, 387
  integral, 295, 356, 387
Water-resistive barrier (WRB), 212–213, 262, 632, 638
Waterstop, 68–69
Water table, 39, 49, 58, 67, 72, 75, 106, 622
Water vapor. *See also* Humidity, relative; Vapor diffusion
  and air leakage, 623, 638
  and the building enclosure, 623, 638–639
  and drained (rainscreen) cladding, 229
  and exterior insulation, 641
  and ice lenses, 51
  and masonry exterior coatings, 387
  and paints and coatings, 226
  and unventilated roofs, 218, 219
  and vapor retarders, 261
  and ventilated roofs, 652
  and water-resistive barrier, 213
Weather barrier. *See* Water-resistive barrier (WRB)
Weeps (weep holes)
  EIFS, 775
  glazing system, 712, 713, 715, 794, 795, 797
  masonry wall, 236, 342, 365, 369, 370, 373, 374, 376–378, 387, 632, 760, 763, 765, 771
  retaining wall, 72
Welded wire reinforcement (WWR), 511–512
  in concrete decking, 375, 437, 440, 551, 558
  in concrete slab on grade, 158, 535, 536
  in precast concrete, 590, 591, 592, 595, 607
Welding
  architectural metals, 485
  structural steel, 411–414
WELL building standard, 8, 240, 263, 816
Wind-borne debris, and window impact resistance, 753–755

Wind load, 34, 454, 457, 468, 623, 624, 651, 710, 712, 713, 718, 752, 763, 764, 798, 801
Windows, 222, 732
  acoustic, 753
  aluminum frame, 737
  blast resistance, 755
  energy performance, 745
  flashings, 220–222, 744
  glass-fiber-reinforced plastic frame, 738
  glazing, 743
  impact resistance, 753–755
  installation, 222, 744
  muntins, 743
  plastic frame, 738
  safety considerations, 752
  steel and bronze frame, 742
  structural performance, 752
  sustainability, 745
  thermal expansion of frame materials, comparative, 738
  thermal performance, 743, 745, 752–753
  types, 732–736
  wood frame, 736
Window-washing, 735, 738
Wood, 80. *See also* Lumber; Plastic lumber; Trees; Veneer, wood; Wood panels; Wood-plastic composite; Wood treatments
  adhesives, 113–115
  biodeterioration, 106–107
  and carbon, 82–83
  environmentally certified, 81–82
  fasteners, 109–114
  naturally durable, 108–109
  rot, 106
  sustainability, 84–85
Wood flooring, 115, 282, 876–878
Wood light frame construction, 152
  balloon frame, 153, 154, 372
  and the building codes, 202–204
  floor framing, 171–175, 185–188
  foundations, 156–164
  framing for increased thermal efficiency, 199, 257, 260
  framing for optimal lumber usage, 199–201
  framing, general concepts, 154–156
  history, 153–154
  lateral force resistance, 178, 181–186
  nailing, 170
  platform frame, 153–156
  prefabrication, 201–202
  preliminary design, 202
  roof framing, 190–198
  subflooring, 154, 156, 173, 175, 188
  sustainability, 156
  uniqueness, 204–207
  wall framing, 176–181, 185–189
Wood panels, 102
  adhesives, 105, 106, 115
  bond classification, 106
  composite, 103, 105
  Exposure 1, 150, 106, 115
  Exterior, 106, 115
  and formaldehyde, 115
  nonveneered, 103, 105
  performance category, 105
  prefabricated, 117
  specifying, 105–106
  structural, 103
  underlayment, 103, 105, 106, 188, 282, 870, 872, 876, 878–880
Wood-plastic composite (WPC), 101, 109, 240
Wood shakes, 218, 220, 231, 657, 671, 672, 691
Wood shingles, 220, 231–235, 237, 239, 320, 657, 671, 672, 691
Wood treatments
  acetylated wood, 108
  fire-retardant treated wood, 109, 129, 691, 822
  glass infused wood, 108
  preservative-treated wood, 72, 97, 107–108, 164, 166, 168, 171, 229
  thermally modified wood, 108
WRB. *See* Water-resistive barrier
Wrought iron, 396, 398, 485
WWR. *See* Welded wire reinforcement (WWR)
Wythe, masonry, 304

Z

Z-flashing. *See* Flashing, Z-
Zinc, 484, 486, 487
Zoning ordinances, 13

WILEY END USER LICENSE AGREEMENT

Go to www.wiley.com/go/eula to access Wiley's ebook EULA.